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OCT 80 J T PARKER, A P THIRUVENGADAM N00014-79-C-0084

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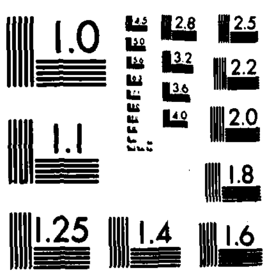

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ENGINEERING, DESIGN AND ANALYSIS SERVICES

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RESEARCH AND DEVELOPMENT OF AN ON-LINE CAVITATING EMULSIFIER FOR THE REDUCTION OF SPECIFIC FUEL CONSUMPTION AND EMISSION PRODUCTS IN U. S. NAVY VESSELS.

Submitted to:

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BRAKE HORSEPOWER	PRESSURE	BOILER AND EXHAUST EMISSIONS
EMULSIFICATION COEFFICIENT	SURFACTANT	STABILITY

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The objective of this program was to perform the research necessary to design, develop, test and evaluate an on-line cavitating emulsification system to determine the fuel saving and emission control potential for U.S. Navy vessels. The advantages of a cavitating emulsifier were the reduction of the engery required to produce the emulsion, the reduction of the size and weight of the equipment, and on-line production capability. In addition, cavitating emulsification technology could be applied to more than one type of combustion system.

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The following engineering parameters were evaluated in an effort to design an on-line energy saving emulsion from a cavitation (ENERSEC) technology system: 1) optimum operating pressure to produce the emulsion; 2) emulsification stability for various grades of fuel oil from Number Two through Number Six; 3) the variation in fuel flow from one piece of equipment to another; 4) optimum water injection method; and 5) the performance advantages of emulsified fuel combustion. The use of ENERSEC technology made possible the production of emulsified fuels without the aid of surfactants.

A basic system design concept was developed and the equipment was tested on three different pieces of combustion equipment. The tests were conducted to confirm previous experiments of the combustion of water-in-Number Two fuel oil emulsions in a diesel engine. Previous experiments had indicated that three to six percent fuel consumption reduction was achievable. This data was confirmed and improved upon.

Additional tests were conducted with water-in-Number Six fuel oil and water-in-Number Four fuel oil. The Number Six fuel oil emulsifier has been operated and evaluated on a 100,000 pounds of steam per hour marine boiler and a 100,000 pounds of steam per hour industrial boiler. Both of these test units indicated approximately three percent fuel savings, and in addition, cleaner boiler operation and reduced maintenance costs were demonstrated. The total savings indicated from these tests were illustrated by an overall operational efficiency improvement of seven percent.

The Number Four fuel oil emulsifier has been laboratory tested. The unit provides emulsions with an approximate two hour stability. The unit has been installed on a boiler of an approximate 50,000 pounds of steam per hour rating. This testing has not been completed at this time.

All of the test combustion systems were fueled by an on-line emulsification system which produces only the amount of emulsion required by the combustion device. The on-line cavitating emulsifier has shown potential for significant reductions in fuel consumption while being able to produce emulsions efficiently at existing system fuel line pressures. This document addresses all of the development and testing completed to date.

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This report is submitted in partial fulfillment of Office of Naval Research contract number N00014-79-C-0084. This initial phase of the research program for the development of an on-line cavitating emulsification system was conducted under the sponsorship of LCDR Harold Martin, Code 470B. The authors would like to take this opportunity to express their appreciation to LCDR Martin for his technical advice and support of this research effort.

In addition the authors wish to thank Mr. James Ballard and Mr. Robert Love of the Delta Steamship Company and Mr. Roger Nesbitt of Georgia-Pacific Corporation for their cooperation and use of their facilities as test platforms.

ABSTRACT

The objective of this program was to perform the research necessary to design, develop, test and evaluate an on-line cavitating emulsification system to determine the fuel saving and emission control potential for U. S. Navy vessels. The advantages of a cavitating emulsifier were the reduction of the energy required to produce the emulsion, the reduction of the size and weight of the equipment, and on-line production capability. In addition, cavitating emulsification technology could be applied to more than one type of combustion system.

The following engineering parameters were evaluated in an effort to design an on-line energy saving emulsion from a cavitation (ENERSEC™) technology system: 1) optimum operating pressure to produce the emulsion; 2) emulsification stability for various grades of fuel oil from Number Two through Number Six; 3) the variation in fuel flow from one piece of equipment to another; 4) optimum water injection method; and 5) the performance advantages of emulsified fuel combustion. The use of ENERSEC technology made possible the production of emulsified fuels without the aid of surfactants.

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1.0 INTRODUCTION

The continuing increases in the price of foreign oil together with presidential orders to reduce oil consumption has prompted research in methods of reducing fuel consumption in existing fleet combustion devices. The U. S. Navy, as a vital link in our national security forces, must remain operationally ready while developing conservation methods or equipment and conversion to alternative fuels.

Although emulsification technology has been available for many years, the advantages of an immediate method of fuel conservation have generated new interest in this technology. The specific technology of energy saving emulsions from cavitation (ENERSEC™) offers specific advantages of interest to shipboard operation. These advantages include the ability to generate within the limited space allocation of shipboard operation, the ability to produce emulsified fuel simply without the necessity for additional additives, the ability to operate and emulsify at normal fuel line operating pressure and the ability to be rapidly installed in an existing fuel line causing minimal downtime. In addition ENERSEC technology provides a method of producing only the amount of emulsion required by the combustion device.

Based upon these operational advantages and the background investigation in emulsions produced by cavitation DAEDALEAN ASSOCIATES, Inc. (DAI) initiated this research program the results of which this report addresses. Under the sponsorship of the Office of Naval Research, this program was aimed at the research required to design, develop, test and evaluate an on-line prototype cavitating emulsifier.

The laboratory research established the ability of the ENERSEC technology to produce stable emulsions with Number Two, Number Four and Number Six fuel oil. The water droplets in these emulsions were approximately three to eight microns (μ) with maximum droplet size of ten microns. This was adequate, as was the emulsification coefficient which indicates the degree of stability, for the on-line type application. The actual demulsification time varied with the grade of oil tested.

The Number Two fuel oil emulsifier was used to supply fuel to the laboratory combustion apparatus and was used to confirm previously attained diesel engine performance information. The Number Six fuel oil emulsifiers were tested on two different types of boiler operations in order to evaluate fuel flow demand differences and modification requirements with respect to unit sizing. The Number Four fuel oil emulsifier was designed for a fixed flow boiler of much smaller system than the Number Six units and this system is under evaluation at this time.

To date, testing on the laboratory system has been completed as has the design of the Number Six emulsifier. Tests are not yet completed on the Number Four emulsifier but enough information has been obtained to confirm the design modifications being evaluated. This report addresses the accomplishments of this research effort, states the conclusions which can be drawn from the data, discusses the equipment designed to confirm the advantages of ENERSEC technology and states the recommendations for additional testing which are a result of the tests conducted.

2.0 BACKGROUND

The engineering staff at DAI has been involved in research work in the field of water-in-oil emulsification for the past five years. Initial research efforts concentrated on the study of emulsion stability of Number Two fuel oil and water. These tests had as their objective the demonstration of feasibility of producing stable water-in-oil emulsions and the demonstration that these emulsions could be burned as a diesel fuel substitute.

In order to evaluate the stability of an emulsion two factors must be considered. The first was the degree of emulsification with respect to time. The second was the percentage of water initially used to produce the emulsion. In order to define the degree of emulsification, the emulsification coefficient was defined. This nondimensional coefficient was defined by the equation:

$$K_e = \frac{V_e - V_w}{V_t} \qquad [1]$$

where:

K_e = the coefficient of emulsification (emulsibility)

V_e = volume of emulsion

V_w = volume of water separated from the emulsion after a specified time, and

V_t = the total volume of fluids used to produce the emulsion

Because stability was dependent upon the percentage of water in the emulsion, the worst case situation was selected for this evaluation. The stability tests were conducted with a fifty percent water-in-fifty percent diesel fuel emulsion. The initial cavitation emulsification apparatus used in these studies is illustrated in Figure 1. The data output from the metering equipment was used to determine the volume of water and volume of oil. The total volume was obtained by the summation of these values. The effluent from the emulsifier was collected and analyzed. The volume of separated water was measured at time t=o and at other specified times.

Because cavitation production was being evaluated a coefficient was defined which would identify the cavitation condition under which the emulsion was prepared. These tests were conducted with several cavitation nozzle orifice variations and for several cavitation parameters. The cavitation parameter, σ, was defined as follows:

$$\sigma = \frac{P_o - P_v}{\frac{1}{2}\rho V_o^2} \quad [2]$$

where:

P_o = emulsification pressure

P_v = vapor pressure of diesel fuel

ρ = density of emulsion, and

V_o = velocity at the emulsification orifice

Figures 2 and 3 illustrate the data obtained in two of the test conditions evaluated in this early research. These figures illustrate the relationship of coefficient of emulsification to demulsification time for various cavitation parameters.

These successes served as motivation for work to determine the optimum emulsification conditions with respect to diesel engine operation and fuel consumption reduction. Two sets of tests were conducted. The first test was conducted in conjunction with another organization using their test facility. In terms of indicated specific fuel consumption and indicated mean effective pressure, Figure 4 illustrates the fuel savings obtained for one of the conditions tested. As these engine tests were conducted the exhaust gases from the diesel engine were analyzed. Figure 5 illustrates the change in NO_x emissions for the same test condition. Figure 6 illustrates the change in Bosch Smoke Number. The Bosch smoke test is a measure of the particulates in the exhaust effluent. This data indicated that as well as reducing fuel usage, emulsification has a beneficial effect upon exhaust emissions.

The second performance tests were conducted as our test facility developed to the combustion evaluation stage. These tests were performed with a two cylinder, twelve horsepower diesel engine. The measurements were recorded in terms of shaft load and brake horsepower rather than indicated values.

The tests were conducted at a slightly lower percentage of water. The results indicated a slightly higher fuel consumption reduction. Figure 7 illustrates the fuel consumption data for these tests at comparable engine operating conditions.

The accomplishments of these tests coupled with the continued increases in foreign oil prices served as motivation for the present research efforts. Another factor which prompted the Navy interest was the fact that cavitation emulsification did not require the addition of costly surface tensioning agents (surfactants). Surfactants were considered in emulsification because they tend to prolong the period of emulsion stability. Long stability would be a consideration if storage of the emulsified fuel were anticipated. However the surfactants tend to be detrimental in two ways when on-line emulsification is the objective. The cost of the surfactant greatly increased the emulsion production expense. In addition the university research community involved in emulsions research has shown the surfactants tend to eliminate the combustion change which is the theorized advantage of emulsion combustion.

The theoretical advantage in emulsion combustion was first proposed by the Russians (1)*. It stated that as the combustion occurred, the water vaporized rapidly forming microexplosions which break the oil into finer droplets allowing more complete

* Numbers in parentheses refer to references at the end of this report.

combustion to occur. This theory and the mechanisms associated with it are being evaluated and researched by the university community here in the United States. This research has photographed a single oil droplet in combustion. Then the procedure was repeated with a ten percent emulsion prepared with surfactants and with a ten percent emulsion prepared without surfactants (2). The results indicated that the presence of the surfactant negated the microexplosions. Photographic evidence of these results taken from the referenced article are shown in Figure 8. This data reinforced the working premise that cavitation produced emulsions were better and less costly than emulsions which included surfactants. Moreover, the above mentioned accomplishments led to the program this report addresses on the design, development, test and evaluation of an on-line ENERSEC technology emulsifier.

3.0 DISCUSSION OF EQUIPMENT AND PROCEDURES

3.1 Diesel Engine Equipment

The first task completed under this research program was the update and extension of the laboratory diesel engine test facility. A larger diesel engine was incorporated as well as exhaust gas analysis apparatus so that, as an emulsification system was developed, it could be fully evaluated. The test cell was arranged to include the diesel engine, dynamometer, and a variable drive system. Figure 9 is a photographic overview of the test cell. Figure 10 is a close-up view of the engine bay showing the orientation of the diesel engine, the dynamometer and the varidrive unit.

The diesel engine selected and installed in the test cell was a two cylinder 25 horsepower engine. The engine was air cooled and high speed rated for maximum 2,000 rpm. The engine was of the compression ignition type diesel engine. Of specific interest to this research program was the fuel flow and supply because the engine provided was atypical of fuel systems incorporated on much larger diesel engines. Because the emulsification device was to be installed for on-line emulsion production, a complete understanding of the fuel system functions was a critical design factor. Figure 11 is the schematic diagram of the fuel flow for the diesel engine as it would normally operate.

The dynamometer used in the test cell was an eddy current dynamometer. As the current to the system was varied the load on the dynamometer was increased or decreased. These changes placed a load upon the diesel engine and the operational performance was measured with respect to these load changes. The dynamometer was used in connection with the varidrive as a control device. The varidrive was installed in order to perform the motoring tests with the engine. These tests were conducted at the same dynamometer load conditions but with the engine and fuel supply turned off. These tests measured the frictional forces required to drive the engine at the specified load condition.

In order to monitor the data generated as the engine tests were conducted, a data acquisition center was established. Figure 12 illustrates that area of the test cell. Within the data center were incorporated the amplifier/readout package, the dynamometer control, the clutch control switches, the exhaust gas analysis equipment, cell temperature gauges, wet bulb barometer for measurement of atmospheric pressure, controls for the cell, exhaust fan and controls for the varidrive system. The readout panel was used to monitor engine rpm, dynamometer load, brake horsepower and engine exhaust gas temperature. The exhaust gas analysis system was used to measure levels of oxygen, carbon monoxide, and carbon dioxide.

3.2 Diesel Engine Emulsification System

The diesel fuel emulsification system consisted of a pump/motor combination, an orifice assembly, flow control valves, flowmeters, tubing and fittings. The pump was a small gear pump rated for three gpm and a maximum pressure of 2,000 psi. The oil and water are pumped to pressure and that pressure was dropped across the orifice as the emulsion was produced.

Two design limitations had to be considered in the design of the diesel fuel emulsification system. The first limitation was the short stability of the emulsion. The production point had to be placed as close as possible to the fuel pump of the engine. The second limitation was a result of the fuel system of an atypical diesel engine. As was illustrated previously in Figure 11, the fuel system had a return line associated with both the fuel filter and the fuel injector manifold. Both of these components of the fuel system take in more fuel than the engine uses and the excess is discharged back to the fuel tank. The transfer of fuel back to the fuel tank could not be permitted with short stability emulsions or water would begin to separate in the storage tank.

Two methods were used at different times in the course of the diesel fuel tests to solve this problem. The first was the addition of a system which removed the water from the oil as it was returned to the fuel tank. This system was incorporated in the return line and as the oil was returned, the water was removed. The water-free oil was returned to storage and the water was pumped to waste. This system is illustrated in the flow schematic for the complete test area as shown in Figure 13. The dewatering solution proved inadequate and was eliminated. The discussion of this design change is included in the "Results" section of this report.

The second method used to solve the return flow problem was to recycle the fuel back into the fuel pump inlet. This modification reduced the requirement for peripheral equipment and simplified the overall operation of the diesel engine test bed. The only change in procedure which resulted was a need to run the engine on straight fuel at the end of each day in order to protect the injectors from water which might have separated out of the oil overnight. Figure 14 illustrates the changes in the overall operation which were the result of this design modification.

3.3 Diesel Engine Test Procedure

Prior to the engine test procedure initiation, the engine was operated in accordance with the manufacturer's operating manual. The manual recommended a period of 50 hours operation at approximately 1/3 rated load as break-in for the engine. This break-in period was observed and upon completion the engine was serviced. The service consisted of changing all filters, changing oil, checking timing and inspection of injector nozzles.

The engine tests were conducted with the engine operating at the factory set timing condition. No modifications were made to any of the normal engine functions other than fuel supply. The factory recommended operating conditions were used in order to eliminate additional variables from the evaluation.

Basically, the diesel engine evaluation tests were conducted in two steps. The first step sequence was used to evaluate the basic operation of the engine at a specified operating condition with regular diesel fuel. The engine was inspected to ensure proper lubrication oil levels and then was started. Just prior to each test run the exhaust fan was started in order to keep adequate air circulation in the cell. Being an air cooled engine, the cell required continuous air exchange. The exhaust fan exchanged the air at the rate of approximately 2600 standard cubic feet per minute. At this rate a complete air exchange was completed in the cell approximately every 15 seconds.

Once the engine was started, it was operated at no-load for a period in order to allow the engine to reach operating temperature. At that time a specified engine RPM and shaft load were applied. With these conditions established, the run data was gathered. For each test condition the brake horsepower, exhaust gas temperature, shaft loading, engine RPM and fuel consumption were recorded. The engine conditions were changed and the procedure repeated until all the required data was assembled.

When the data for the basic fuel operation was complete, the entire test sequence was repeated with the engine operating on the emulsified fuel to be evaluated. In the emulsified fuel test sequence the same data was recorded so that direct performance comparisons could be made. In addition to the previously discussed data, nozzle orifice parameters, the pressure drop across the orifice and the percentage of water were also recorded. This data was used to define the emulsion produced and the cavitation condition at which production occurred.

The data which resulted from the two test sequences was analyzed and comparative data summarized. This data will be discussed in detail in the "Results" section of this report.

3.4 Number Six Fuel Oil Test Equipment

Realizing that the Navy spends as much money on facility boiler operation as on fleet operations, testing and design efforts were initiated to develop an emulsification system for Number Six fuel oil and water. To accomplish this design effort, laboratory apparatus which simulated the boiler fuel feed system was used. This loop system consisted of an oil supply tank, fuel oil heater units, an oil transfer pump, flow control valves, flow monitoring equipment, temperature gauges, pressure gauges, safety systems and flanged connections for the emulsifier. Figure 15 illustrates the fuel supply system simulation loop used in the Number Six emulsifier design efforts. This loop was constructed of two inch diameter Schedule 80 pipe in order to handle the operating pressure and temperature.

The transfer pump in the loop was a positive displacement heavy duty screw pump. The pump was rated for maximum pressures of 500 psi. The pump was driven by a 20 horsepower electric motor. This combination produced a maximum flow rate of 65 gpm which simulated boiler systems rated up to approximately 200,000 pounds of steam per hour.

The storage capacity of the system was 500 gallons. In addition to the storage tank another 500 gallon tank was included for waste emulsion disposal. Both of these tanks were insulated and heated. The heaters were used to raise the oil to test temperature. The maximum temperature obtained was 150°F. Because of the dangers of working with hot oil, safety systems were part of the loop. A pressure relief valve was installed so that, if the pressure reached relief level, the oil would be dumped automatically into the waste tank. For most operations this valve was set to relieve at 400 psi.

A control panel was assembled in the loop which contained oil flowmeter readout, water flowmeter readout, oil pressure gauge, oil temperature gauge, water pressure gauge and the pump control switch. In addition to the meters and gauges, the panel also contained two shut-off valves which were used to protect the gauges when not in use. The panel was located next to the main flow control valves for easy operator access and visibility. Another feature of the loop was the sampling valve which was located just to the left of the control panel. This valve was used when an emulsifier was being tested to draw off samples of the emulsions which could be analyzed.

3.5 Number Six Fuel Oil ENERSEC Systems

There were essentially two design concepts assembled and evaluated in this activity. The first system concept was to produce a fixed emulsion percentage at a fixed flow rate. This concept would be applicable if the system was to be designed specifically for each application. The second concept was to produce a universal design which, with minor modification, would produce emulsions of varying water percentage and variable fuel flow rates. This concept would be adaptable to any application without the necessity of complete redesign. The discussions in the next two subsections elaborate on these designs and describe the systems produced.

3.5.1 Fixed Flow System Design

This unit design was the initial attempt to scale up the laboratory system to meet a specific need. As a result of the application consideration was not given to the universal nature of the system. The system was to produce emulsified fuel at a fixed rate of 30 gpm. The system would take incoming oil, add a fixed percentage of water, pass the mixture through a cavitation orifice, pump the emulsion back to line pressure and return the emulsion to the supply line for use in the boilers. Working with a commercial steamship company, the unit was to provide emulsions for two marine boilers generating at cruise condition.

To accommodate the flow rate requirement of the two boilers, the system was constructed of welded joint pipe and fittings of the tube steel rated for the temperature and pressure in excess of operating conditions. The only nonwelded fittings were those where the unit would be flanged into the boiler oil supply line and the flanged section where the cavitating orifice was installed. All of the piping used was two inch diameter. A motor-pump combination was selected which would provide the flow rate and pressure the system would require. In addition, the pump was positive displacement screw-type which was rated to generate at pressures in excess of the supply line pressures and was capable of continuous duty in oil temperatures up to 200°F. The motor which powered this unit was a totally enclosed fan cooled motor rated at 25 horsepower. This type of motor was selected for safety of operation in a boiler room environment. The potential hazard of fire was one of the primary considerations of this design and a totally enclosed motor eliminated the potential of ignition as a result of exposed motor coils. Figure 16 illustrates the unit as it was assembled for installation in the test situation for which it was designed. Both of these systems and the variable flow system discussed in the next section have been reviewed by the U. S. Coast Guard and approved for maritime applications. This approval was given after an examination of the design, inspection of the equipment safety devices and inspection and certification of the welded connections.

3.5.2 Variable Flow System Design

The operational parameters were different in the design of this unit when compared to the fixed flow system. The constant design parameters were the production of emulsions without surfactants, the production of emulsions at no more than fuel supply line pressure and maintain a simple and easily maintained piece of equipment. The safety requirements were also taken into consideration in the design of this equipment.

The second unit was designed to meet a different set of objectives. The main objectives in the design of this system were first to produce a semiuniversal design that might be applied to different applications and second to produce variable percentage emulsions and pump varied amounts of fuel to meet changes in the boiler demand. The basic configuration of the unit was unchanged. Oil passed into the system from the supply line through a flowmeter and the orifice assembly into the pump and back into the supply line to move on to the boiler.

The two major changes in the design were made with respect to the water addition and emulsion flow within the unit itself. With respect to oil/emulsion flow, the unit incorporated an internal flow loop and the flow rate of the pump was sized just slightly larger than the maximum demand of the boiler. When the boiler was operated at less than maximum, the excess output of the ENERSEC unit bypassed within the internal loop until the demand of the boiler changed. The oil flow into or out of the ENERSEC system was maintained at boiler demand setting. Figure 17 illustrates these changes.

The changes in the water addition system were more sophisticated in order to maintain any set percentage of water addition. To accomplish this task a flowmeter and motorized control valve were incorporated in the water line. The control system designed to monitor the water used the frequencies from the oil flowmeter and the water flowmeter to establish a bias voltage. Based upon that bias voltage the motorized valve opened or closed to increase or decrease water flow. The controlling frequency was that of the oil flowmeter so that the water added was always the amount required for the set percentage. In addition the percentage of water added was based solely upon the flow of oil into the emulsification unit.

The electronic control box designed for this unit had three digital readout panels. Each of the panels read out a different function. The center readout panel indicated the meter reading in gallons per minute of the oil. The righthand panel indicated the meter reading of the water flowmeter in gallons per minute. The third panel constantly read the percentage of emulsion which was being prepared. Figure 18 illustrates the readout and selection pace of the control box. Figure 19 illustrates the variable flow ENERSEC system as it was ready to install in the test boiler.

3.6 Number Six ENERSEC Test Procedure

Within the laboratory environment the test procedure for the Number Six fuel oil emulsifiers was the same. However, each system was handled under quite different circumstances in actual on-line field trials. As the system was assembled, the laboratory test procedure was initiated. The first step in this procedure was the pressure test of the entire system. The assembled unit was installed in conjunction with the laboratory supply loop and operated at the designed operating pressure for a period of at least five hours. This operation was performed without any addition of water. This procedure was used to accomplish several quality assurance checks. The system was monitored to make certain it would operate at designed pressure settings. The system was inspected to ensure that all welds were secure and the system had no leaks or malfunctions. The last check was to ensure that the various safety circuits all functioned properly.

While the main unit was operated on straight Number Six oil for assurance, the water system was operated independently. The oil flow control was used to supply the frequency information but the water was dumped to waste rather than added to the oil. In this manner the amount of waste emulsion was kept to a minimum. As the oil flow was varied, the water valve was monitored to ensure proper opening and closing. The water flow was measured to make certain the calibration settings on the unit were correct and accurate.

Once the checks, inspections and calibrations had been completed, the water was attached and emulsions produced. The emulsifier was run long enough to ensure that all systems functioned as a unit. During this final laboratory operation samples of the emulsion were taken in order to perform the microscopic analysis. This analysis determined the droplet size of the water in the emulsion at the time it was produced and the degree to which the water-in-Number Six fuel oil emulsion was stable.

With the laboratory test of the ENERSEC unit complete, each was installed in its respective on-line test bed and evaluated. However, each of these evaluation procedures was unique as a result of the differences in application as well as the systems. For this reason the discussion of each on-line trial must be discussed independently.

3.6.1 Fixed Flow Design Operational Evaluation

The fixed flow unit was installed in a commerical steamship boiler room. The unit was installed into the feed line between the fuel heater and the boilers. The unit was installed in a way that it provided emulsion to both the port and starboard boilers. Each boiler was rated at 100,000 pounds of steam per hour. However, the owners were only interested in two factors. First, they wanted to see if acceptable emulsification was obtained without the requirements for surfactants and a high pressure system in the boiler room. Second, they were interested in the cleaning aspects of emulsified fuel burning. Operation was to provide clean, high efficiency boiler performance over the complete cruise duration.

For the above reasons, the fixed flow system was designed to be engaged when the vessel reached cruise condition and operated only in that condition. The boilers were monitored during operation by keeping records of the superheater output temperature. Decreases in superheater output indicated initiation of a scaling condition in the boiler. If the superheater temperature remained at or near the rated value the emulsion was having the desired effect of removing or preventing any boiler scale.

3.6.2 Variable Flow Design Operational Evaluation

The variable flow unit was installed in a totally different situation. The unit was designed to provide continuous emulsified fuel to a single boiler in an industrial installation. The particular boiler was one which was used for idea studies and to provide additional steam in a process application. The studies conducted with this boiler were evaluations of process modifications to be incorporated later in the main plant boiler system. The single boiler was rated at approximately 100,000 pounds of steam per hour.

In this installation an evaluation of the effects of emulsified fuel was conducted. Both the water percentage and boiler adjustments were monitored in order to obtain maximum fuel savings as well as fireside maintenance advantage. This unit was used throughout the complete range of boiler load condition. The percentage of water was varied through its complete range in order to determine optimum percentage for this boiler.

In addition to the other evaluations, the effect of emulsified fuel on the stack gas effluent was monitored. The objective of these tests was to determine if the use of emulsified fuel would aid in meeting the local and federal Environmental Protection Agency (EPA) clean air standards. The total information of these tests would provide documentation of laboratory claims with respect to ENERSEC utilization from actual field testing. The results of these tests are contained in the discussion of results section of this report. In addition these tests would show the readiness of the equipment for navy evaluation and acceptance testing.

In the case of both the fixed and variable flow systems, the units were installed in the test bed between the feed pump and the burners. This installation took advantage of the boiler facility's existing fuel heaters and transfer pumps. In this installation configuration the on-line emulsification equipment was as compact and lightweight as possible. Size and weight of the ENERSEC system were important considerations for potential shipboard installations.

4.0 DISCUSSION OF EXPERIMENTAL RESULTS

The design and performance data obtained from the laboratory and field tests was reviewed and analyzed. From the design information review, process and assembly modifications were initiated. These changes incorporated the best of all on-line configurations in order to standardize a design which was suitable for most navy applications.

The data from the laboratory and field tests was analyzed and summarized in order to document the performance of ENERSEC technology. The laboratory data summarized the research and system design with respect to Number Two fuel oil. The field test data describes the performance of on-line ENERSEC emulsification with Number Six and Bunker C fuel oil. The following subsections discuss each of these test results independently.

4.1 Diesel Engine Emulsifier Test Results

The discussion of diesel engine emulsifier test results included the actual data gathered as well as the several design changes of the Number Two fuel oil emulsifier system. The design changes were the result of the simplification of the apparatus from a change in operating procedures. The data obtained from the testing was gathered to verify previous test results. This data and the design modifications which produced a much simpler emulsification system for diesel fuel will be discussed in detail in the following subsections.

4.1.1 System Design Modifications

The first modification was the result of operational necessity. The laboratory system had incorporated a dewatering system which would reduce the amount of excess or waste emulsion produced. The dewatering system removed the water from oil, returned the oil to storage tanks and pumped the water to waste. The modification eliminated this dewatering device.

There were two reasons for the elimination of this system. The first was the fact that, in practical terms, the dewatering equipment did not remove all of the water. This meant that for each test operation a small percentage of water was added to the oil storage tank. This fault in the equipment could have been corrected if the operational sequence was adjustable. However, the dewatering equipment is a very complex system with no simple way to override its automated functions. For that reason it was eliminated. In addition, the fault in the equipment prevented adequate determination of the amount of water in the emulsion as well as maintenance problems in the storage system. Returning water to the storage tanks also contaminated the primary oil supply.

The second reason the design modification was undertaken related to the main objective of on-line utilization. The size of the dewatering equipment required to handle the quantity of emulsion produced in the laboratory would have limited the use of this phase of emulsification technology to stationary engines. In addition, the dewatering system increased the complexity of the overall system and the maintenance requirements of the emulsification apparatus.

The modification of the diesel emulsifier encompassed a slight change in the engine fuel supply system as well as the elimination of the dewatering device. The excess fuel from the injector head is used as a cooling mechanism and therefore must be maintained. The engine fuel filter system was bypassed completely. Fuel filtration was incorporated prior to the fuel entry into the emulsifier. The injector return flow was passed through a closed loop and introduced into the area of cavitation. This closed loop provided adequate cooling to the injectors as well as a method of preventing demulsification of the emulsion in the loop. Excess emulsion not accepted by the engine was returned to the emulsifier pump inlet and recycled. In this manner production was controlled by engine demand. This design modification greatly reduced the system size and complexity. In addition, the smaller system design permitted the potential operation with any diesel engine, stationary or mobile.

The second design modification was based upon an evaluation of emulsification procedures tested previously. Prior to this evaluation, the production of Number Two fuel oil emulsions had been accomplished at high pressure. Pressures between 1500 and 2000 psi were used. These pressures were used in order to establish stability limits. For these tests, minimum stability was required and the operational parameters governing production were changed. The objective was to establish minimum operating pressures which provided sufficient stability for on-line production and combustion.

As a result of these procedural changes, the production pressures were reduced by an approximate factor of three. Satisfactory emulsions were produced at pressures within the range of 300 to 500 psi. This factor and the associated design modifications reduced the size and energy requirements of the emulsification equipment. In addition this reduction of the operating pressure permitted the use of less sophisticated and less expensive equipment than that normally associated with high pressure hydrodynamic systems.

These operationally initiated design modifications were incorporated in the laboratory test apparatus. The redesigned system was used to verify the data obtained from previous diesel engine performance evaluations. This data is reported in the following subsection.

4.1.2 Diesel Emulsions Performance Test Results

In order to verify the previous laboratory experimental results under the new design conditions, one previously tested emulsion was selected for engine performance evaluation. Prior to the operation on emulsified fuel, the engine was monitored while using standard Number Two diesel fuel. These tests established the engine base line performance data which was then compared to the emulsified fuel test information. The engine was operated under the same RPM and load conditions to be tested with the emulsion.

The first test sequence was conducted with the engine operating at a mid-range RPM of 1200. A no-load, 25 pound load, 35 pound load and approximate maximum load conditions were evaluated. Several individual runs were made at each test condition in order to ensure the accuracy and define the spread of the data generated. At each test condition at least two exhaust gas samples were analyzed. This same test procedure was repeated at an RPM of 1800 which was the maximum rated continuous duty RPM for the engine.

These procedures were then repeated with the emulsification system operational. An emulsion of ten percent water in diesel fuel was selected and evaluated. The only difference in the two test sequences was the additional data gathered for the emulsions tests. That data was necessary in order to define the cavitation conditions of emulsion production. The data was analyzed and plotted for each RPM. For direct comparison with and without emulsified fuel, composite plots were prepared which superimposed and summarized the data obtained.

Figure 20 illustrates the fuel consumption data for the diesel engine operating at 1200 RPM. The data is expressed in terms of brake specific fuel consumption (BSFC) in pounds of fuel per brake horsepower-hour as a function of engine load expressed in brake horsepower. The brackets on the data indicate the confidence limits of each data point. The limits were established by statistical analysis of the individual data points for each load condition.

Two sets of data appear in this figure. The first represented by the circles was the fuel consumption of the engine burning Number Two diesel fuel. The second set of data represented by the squares was that obtained with emulsified fuel. The numbers which appear between these points indicate the percentage change in BSFC. A positive sign indicated an increase in consumption and a negative sign indicated a decrease.

The 1200 RPM performance test data indicated that the design modifications improved fuel consumption in the engine by a factor of approximately three over previous performance test data. Earlier tests had shown reductions ranging from three to six percent. With the system modifications and operational changes, the fuel consumption reductions ranged from eleven to fifteen percent at the 1200 RPM test condition.

A similar trend in the data was obtained with the engine operating at 1800 RPM. Although the engine was rated for 2,000 RPM maximum, the continuous duty maximum was 1800 RPM. At that RPM an engine load of 19.0 horsepower was maximum load. Tests were conducted from "no load" to this maximum load condition.

Figure 21 illustrates the summary data for the fuel consumption tests at 1800 RPM. Again, fuel consumption is plotted as a function of engine load. The trend toward greater reductions in fuel consumption was obtained. However, the reductions obtained with the engine running at 1800 RPM were not as consistent as the 1200 RPM data. In addition the maximum percent reduction was not as high. For the 1800 RPM conditions, reductions ranged from 4.0 to 11 percent. The precise reason for the lower reductions in fuel consumption have not been determined. However, the effect of test cell temperature was considered as the primary contributing factor. The air cooled engine develops considerable heat at the high RPM and high load conditions.

The engine was equipped from the factory with a thermal cut-off safety switch. This device was installed to protect the engine from overheating. As the 1800 RPM tests were initiated, a procedure change was required. It became necessary to reduce the test run duration from fifteen minutes to ten minutes. This reduction in test time was required in order to prevent engine thermal cut-off during the test sequence. This change was made. However, the reduction in run time reduced the accuracy of the measurements made with respect to time. These factors contributed to the instability of the 1800 RPM data. Further testing is anticipated after modification of the Cell Air Exchange Apparatus.

At the conclusion of the test sequences, the injectors were removed from the engine and inspected. The injectors were coated with a minor carbon deposit. The operating manual stated that this was normal for the number of run hours on the engine. The injectors were cleaned and the deposits removed. Inspection of the injectors showed no signs of wear of any kind. Other than the carbon deposit, the injectors were in original condition. This inspection tended to confirm that the emulsion was remaining stable through combustion and therefore no water damage to the injectors had occurred.

The exhaust gas emissions data was summarized for each test sequence. The data showed that for both CO and O_2, emissions were decreased at the high load condition. However, the effect upon CO_2 emissions were negligible over the range of load at each RPM. The analysis equipment gathered emissions in terms of percentage of the total sample. The data was plotted for each RPM as a function of engine load. The 1200 RPM exhaust gas data summary is illustrated in Figure 22. The 1800 RPM information showed similar general trends. More than anything this data pointed out the need for more sophisticated exhaust gas sampling apparatus.

4.2 Fixed Flow Design Operational Test Results

The fixed flow system was installed and tested in a marine operation in order to determine the maintenance effects of emulsified fuels. In addition, tests were conducted to determine the degree of stability of the water-in-Number Six oil emulsions. These tests were conducted by DAI and again by the shipowner.

The demulsification of the water-fuel oil emulsion is critical to the location of the ENERSEC system. The unit must provide fully emulsified fuel to the burner in order to make maximum use of the microexplosion phenomenon which occurs. Figure 23 illustrates the results of one of the demulsification tests conducted. At a magnification factor of 400 two photomicrographs of water-in-Number Six fuel oil are shown. Sample 1 is a photograph of the emulsion taken within minutes of its production. This sample indicated droplet sizes ranging from 1 to 25 microns and the average droplet size of approximately 5 microns.

The second sample is of the same emulsion after a four month settling time. There was no apparent change in the droplet size over that time period. The largest droplets were still approximately 15 microns and the average size remains approximately 5 microns. These photomicrographs illustrate the stability of the water-in-Number Six fuel oil to be more than adequate for on-line application. The ENERSEC system can be installed at any distance from the boiler and still deliver stable emulsion to the burner.

Similar evaluations by the facility personnel over a three month period reported similar findings. In their evaluation, two samples were analyzed; one from the top and one from the bottom of the oil storage container. The summary of those findings were:

1) There are more water droplets present at the bottom of the oil than at the top.

2) Between 85 and 90 percent of the water droplets, both at the top and at the bottom of the oil were less than five micron in size.

3) There are no more of the larger droplets in the bottom than in the top of the sample.

4) More of the larger droplets of water were observed in the sample than at the time of examination three months previously. This indicates some coalescence of the water over the three month period.

5) In general, the total number of water droplets was less at this time than at the time of the previous examination. This is further indication of coalescence.

The statements made in this analysis however indicated that after three months the emulsion stability is still well within the combustion condition required for an on-line system. The actual time for on-line delivery approaches at maximum twenty minutes. The emulsion created by the on-line cavitating emulsification system was stable for far longer than necessary for use with average boiler feed systems.

The second and primary areas of analysis accomplished with the fixed flow unit was the determination of the maintenance benefits obtained from combustion of emulsified fuel. Without the ability to open and inspect the boiler the method used to determine scaled condition was to monitor the change in superheater output temperature. As scale developed in the boiler a drop in superheater temperature was recorded. The drop resulted from additional heat absorbed by the scale rather than transferred to the superheater. Figure 24 is an extract from the operations log which indicate an approximate 100° reduction of the superheater output as scale developed on the fireside of the boiler. The rated superheater output temperature for these boilers was approximately 950°F. This 100° temperature drop indicated inefficient boiler operation.

The installation of emulsification equipment was completed and data recorded in two ways to document the improved maintenance characteristics of emulsified fuel combustion. The first method used to verify the difference was the records of superheater output temperature after the initiation of emulsified fuel combustion. This was accomplished by usage of the operative log. Figure 25 is an extract from that log indicating that on emulsified fuel the superheater temperature remained at or near rated value. This maintenance of rated superheater output temperature indicated no loss due to scale formation while operating on emulsified fuel.

The second method used to verify this self-cleaning characteristic of emulsion combustion was photographic. Prior to the initiation of emulsifier operation the boiler was opened and its fireside photographed. The vessel then left port on a 45 day voyage. Upon return to port the boiler was again opened and another series of photographs of the same section of the fireside were taken. One example of these before and after photographs are shown in Figure 26. These photographs illustrated the fact that emulsified fuel prevented additional scale formation. In addition, this data illustrated that operation with emulsified fuel also causes the scale in the boiler to leach off the tube walls. This removal of existing scale could be accomplished in as little time as 45 days. This same time period was all that was required to cause a 100^0 temperature loss while operating on Number Six fuel oil.

Because this system was designed and utilized only at times when the vessel was at cruise condition, the total maintenance benefit was not realized. In addition it was not possible to evaluate fuel consumption on this unit because a cruise condition and maneuvering are different fuel consumption considerations. To adequately identify the fuel consumption potential the variable flow design configuration was conceived in order to keep the emulsification system on-line 100 percent of the boiler operation time.

4.3 Variable Flow Design Operational Test Results

This design configuration was assembled and tested in order to evaluate design modifications which would permit the emulsifier to be operational 100 percent of the time the boiler was operational. The testing was performed with the system installed in the supply line for a 100,000 lb/hr. industrial package boiler.

This boiler was an "A" type boiler generating steam at 400 psi amd 700°F at full load conditions. To ensure that the evaluation was based upon fuel variations only, the boiler was rebuilt and retubed prior to installation of the variable flow emulsification unit. In order to compare the performance of the boiler with and without emulsified fuel, the previous three years' performance records were used as base line data. This data was compared to the results obtained from emulsified fuel tests. These tests were conducted during boiler operation over an approximate six month period. The summary statements of the findings of this comparative analysis are listed below:

1. The evaporation rate expressed in pounds of steam per gallon of oil burned has increased approximately 4 lbs/gal. This represented an efficiency increase of three percent. Another way of expressing this data was in terms of fuel consumption. For the same steam output

as obtained with standard fuel, a three percent reduction with emulsified fuel was obtained. This data is illustrated in Figure 27.

2. The improvement in evaporation rate appeared to remain constant from 30 percent boiler load to the full load condition. This consistency meant that for most boiler operating conditions three percent fuel consumption reduction was realized.

3. Soot blowing frequency of operation was reduced from once per eight hour shift to once every 24 hours. This reduction represented an approximate savings of 27,000 pounds of steam per day. In terms of fuel savings, pounds of steam was converted to BTU's and BTU's converted to equivalent quantity of fuel. This operational change represented an additional fuel consumption reduction of 4.5 barrels of fuel per day.

4. Atomizing steam to the oil burners was reduced using emulsified fuel. With standard oil atomizing steam differential pressure was 20 psi. Using emulsified fuel, this differential pressure was reduced to 10 psi. This change represented an additional 3,000 pounds of steam per day saved. Using the same conversions mentioned above, this was equal to 0.5 barrel a day additional fuel savings.

5. The total improvement indicated above must be summed in order to measure the fuel conservation realized from emulsified fuel. In terms of fuel savings this data indicated an approximate four percent fuel savings. The boiler was rated for approximately 500 barrels a day consumption and a total savings of approximately 20 barrels a day was realized.

6. Furnace cleanliness and its effect on fuel savings or boiler efficiency can only be estimated. These factors of heating surface fouling, draft loss changes and boiler performance must be measured over long term and recorded.

7. Furnace fireside wall deposits were light and relatively nonadherent. The bulk of the deposits were swept away with a straw broom as illustrated in Figure 28 and the remaining tubes appeared to stay clean and bright.

8. Exit stack gas temperatures were reduced 35°F in the first fifteen minutes of emulsified fuel combustion. Long term evaluations will determine the actual effect upon exit gases.

9. Based on stack testing, observations and base load conditions, with emulsified fuel, particulate emissions were reduced approximately 50 percent. This factor may have significance when boiler operations are required to meet federal and local clean air standards.

This data illustrated that the on-line emulsification technology was capable of producing, at minimum, a three percent reduction in boiler fuel consumption.

4.4 Finalized System Design Results

From a design standpoint the previously discussed test sequences did point out certain operational changes which would provide a more functional system. Based upon the performance data and comments from the boiler operators, design efforts were initiated to incorporate the best characteristics of the two prototype systems evaluated. In addition the operational considerations of size, weight, reliability and ease of maintenance were considered as the system designs were finalized. These parameters were considered based upon the realization of limited space in shipboard boiler rooms. The design changes would permit the system to operate with boilers with fuel flow rates from 10 to 100 gpm with minor modification.

The two major changes in the system were in the water supply system and in the general piping configuration. The water system modification was made in order to use the simplicity of the fixed flow system and the versatility of the variable system. In addition, certain modifications in the variable flow design water controls were required to correct unanticipated problems encountered with the variable flow system in field tests.

Under field conditions two situations were encountered. The first situation was with respect to the feed water to the monitoring equipment. If the upstream water was interrupted, the monitoring system demanded more water and opened the control valve. When the water was reestablished an excessive amount of water was added to the oil before the valve closed to the proper setting. This situation created flame-out in the burner which was hazardous and therefore must be corrected. The fixed flow system was either "On" or "Off" and this concept was incorporated in the design modification.

The second situation was a result of the optical water flowmeter in the water line. This meter was affected by the quality of the water in the system. Dirty water blocked out the turbine so the monitoring system misread the amount of water being added. This situation was corrected on site through the use of extensive filtration of the incoming water. The design modification was required in order to eliminate the maintenance problems of the filter and correct the difficulty associated with optical flow systems.

The design modification incorporated in the final configuration eliminated the need for a water meter. A monitoring system was designed which operates on the frequency of the oil flowmeter only. This frequency determined the amount of water required and opened or closed the monitoring device accordingly. When the boiler is operated at very low flow rate no water is added. In this manner it is impossible to add an excessive amount of water to the fuel oil. These modifications were tested under laboratory condition and function very well in those tests.

The piping configuration was rearranged in this design effort in order to compact the system. To accomplish this size reduction, the piping was arranged in a more compact fashion. In addition, the water monitoring and control equipment was eliminated as a separate package and installed as an integral part of the unit control boxes. The unit was redesigned to occupy floor space of less than five feet in length and less than two feet in width. The height of the unit above the floor remained at less than 50 inches. Figure 29 illustrates the first system assembled of this new design. This unit is being evaluated in the laboratory at this time.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The evaluations of the various emulsification system design concept have produced the data discussed in the previous section of this report. A thorough analysis of the data produced the conclusions and recommendations which follow. The functional capability, reliability and performance of the online cavitating emulsifier was reviewed from both the laboratory and operational test conditions. The results of these evaluations have confirmed previous performance expectations and indicated equipment modifications which have improved and simplified systems operation. As a result an emulsification system has been designed which is ready for on-line navy evaluation. The following conclusions and recommendations summarize the salient findings and address the actions to be undertaken in order to transfer emulsification technology to the navy for operational implementation.

5.1 Conclusions

The conclusions stated are based on the laboratory and field testing as well as the design efforts. The objective of this program was the design of an emulsification system which would reduce fuel consumption and exhaust emissions when used in conjunction with navy combustion devices. With this objective in mind, a review of the data gathered in this research and development program has produced the following conclusions:

1. Stable emulsions of water-in-fuel oil were produced in on-line equipment at existing fuel system pressures.

2. The Number Two fuel oil emulsions were stable for periods up to ten minutes when produced at supply line pressures of less than 500 psi.

3. The Number Six fuel oil emulsions were stable for several weeks at production pressures of 500 psi or less.

4. As a result of the short stability of the Number Two fuel oil emulsions, emulsification equipment must be located as close as possible to the combustion chamber.

5. The Number Two fuel oil emulsions when used in a diesel engine reduced engine fuel consumption by approximately 10.5 percent. This data confirmed previous test results showing reductions ranging from three to six percent and expanded that reduction to the range from four to fifteen percent.

6. The short stability does have no apparent effect on the fuel consumption of the engine.

7. Diesel engine exhaust emissions of carbon monoxide (CO) were reduced at high load when using emulsified fuel.

8. Emissions of Carbon Dioxide (CO_2) were relatively unchanged when emulsified fuel was combusted.

9. More sophisticated exhaust gas analysis apparatus is required in order to totally characterize exhaust emissions.

10. For on-line emulsification to be diesel engine implemented, minor modifications of the engine fuel supply are required. The engine fuel filter system must be eliminated and the filtration must occur prior to the emulsification.

11. In each emulsification condition evaluated, the parasitic energy to produce the emulsion is less than 0.05 percent of the output energy of the combustion system. This means the effect of the energy required to produce the emulsion is negligible.

12. The use of Number Six fuel oil emulsion reduces boiler fuel consumption, at a minimum, three percent. The range of improved fuel economy is dependent upon many factors but ranges between the same three to six percent seen with early diesel fuel experiments.

13. The use of Number Six emulsions has the added benefit of reducing the maintenance requirements of the boiler fireside. This occurs through the control of the amount of scale which forms as a result of combustion of high mineral content oils.

14. The use of emulsified boiler fuel permits a reduction in the atomizing steam which is an additional savings in the overall operation.

15. The particulate in the stack gas effluent is reduced as much as fifty percent when emulsified fuel is burned.

16. The smoke emissions for the stack are directly proportional to the boiler excess air setting. When emulsified fuel is burned, the excess air setting for the boiler must be reduced. From observation if this adjustment is made, the smoke is completely eliminated when emulsions are burned.

17. Boiler performance is maintained at or near rated values for extended periods when emulsions are burned. This was indicated by the ability to maintain rated superheated output temperatures for prolonged periods (approximately forty-five days).

18. Design modifications have provided a system which will emulsify fuel for any boiler with fuel flows ranging from 10 to 100 gallons per minute.

19. On-line cavitation emulsification (ENERSEC) systems can be installed with minimal downtime of the primary combustion system.

20. On-line ENERSEC system design permits the production of emulsions as they are needed and without the requirement of costly surfactants.

21. The on-line ENERSEC technology has permitted the design of a compact, lightweight, low maintenance, low energy system for the emulsification of oil and water which is ready for implementation in navy boiler system.

5.2 Recommendations

The laboratory test results, the field activities, the design efforts and the analysis of all of the factors have produced the recommendations which follow. Some of these recommendations are related to specific systems while others are of a general nature with respect to emulsification technology.

1. It is recommended that an ENERSEC system which incorporates the final design modifications be installed on a navy test bed boiler in order to demonstrate to cognizant navy personnel the readiness of this technology for boiler system operations.

2. It is recommended that additional developmental work be initiated with respect to diesel engine applications. Although the basic concept has been operational in the laboratory, additional system parameters must be identified in order to design a system to operate with the wide range of different diesel engines in naval service.

3. It is recommended that more sophisticated exhaust gas analysis be incorporated in the laboratory in order to evaluate the unburned hydrocarbons and oxides of nitrogen. These emissions, as well as particulates, are of primary interest in diesel engine emission controls.

4. It is recommended that additional research be conducted at a boiler facility in order to evaluate the effects of emulsified fuels on systems effluents. Of specific interest are the effects of emulsions technology upon the emitted oxides of sulphur.

5. It is recommended that design efforts be undertaken to establish the precise relationship between the percentage of water in the emulsion and the excess air setting of the boiler. These

efforts should concentrate upon the design of an excess air-percent water interlock and control system.

6. It is recommended that research be conducted which will establish whether steam atomization is required with emulsified fuel. The micro-explosion mechanism associated with emulsification may be sufficient to permit the elimination of atomizing steam which would further increase the fuel savings which results from emulsified fuel combustion.

7. It is recommended that the design efforts with respect to diesel fuel emulsification concentrate on the operational problems associated with the relatively short stability of those emulsions. The systems must incorporate a control circuit which eliminates the emulsion from the engine fuel system prior to long duration downtimes in order to prevent wear and corrosion.

8. It is recommended that boiler burner nozzle design be analyzed with respect to emulsified fuel. More efficient combustion of emulsions may be possible if the burner nozzle is designed to function with the emulsion.

9. It is recommended that emulsification combustion flame patterns be evaluated as a solution to the problem of flame/tube impingement. The erosion and replacement of boiler tubes damaged by flame impingement may be corrected by emulsified fuel combustion.

10. It is recommended that cavitation orifice design technology be investigated in order to maximize the stability of Number Two fuel oil emulsions without changing the other system related parameters. The intensity of cavitation increases tend to increase the stability of the emulsion. For this reason, changes in orifice design which increase intensity will increase emulsion stability.

11. It is recommended that research be initiated to evaluate the combustion effects and ecomonic factors associated with the use of emulsification technology as a means of oil replacement. A combination of water and other combustible material such as alcohol may provide additional fuel savings and thereby reduce the dependence on foreign oil.

6.0 CONTINUING AND PROJECTED DEVELOPMENTS

As this research effort has drawn to a conclusion certain of the immediate potentials of emulsification have been continued in-house. In addition other efforts of emulsion research are projected as the commercial market for ENERSEC systems increases. This section of this report addresses the continuing and projected design efforts and developments.

The research work which has been continued has addressed the stability of other oil grade emulsions. Specifically, Number Four fuel oil has been emulsified. Just as Number Four oil is a grade midway between Two and Six, the stability of its emulsions falls midway between those of Two and Six. The working objectives for Number Four oil were the same as previous tests, that is, the production of emulsion at line feed pressure. At these production pressures several emulsions were prepared and photomicrographs taken. The emulsions of Number Four oil remained stable for up to two hours before any sign of coalescence was noticed. Figure 30, Sample A, shows the emulsion immediately after production and Sample B is the same emulsion after two hours.

The stability research in Number Four oil led to design efforts to miniaturize the boiler emulsifier designed under this program. The new design was to handle fuel flow of approximately five gallons per minute. Figure 31 illustrates the prototype system assembled as a result of this design effort.

This system is undergoing evaluation at this time. The one piece of information obtained from this evaluation was the physical difference of emulsion combustion. Figure 32 is a photograph of Number Four fuel oil in combustion. This can be compared with the emulsion of Number Four fuel oil in combustion. This comparison illustrates that a hotter and more brilliant fire results. Figure 33 is a photograph of the emulsion in combustion. The same combustion system was used in each test.

Projected design efforts are to design a universal system for small boilers which have fuel flow from one to ten gallons per minute. In addition, it is anticipated that further miniaturization will be designed in order to provide a system which is capable of functioning with residential size furnace systems.

The other area of continued development is related to the laboratory research capability. A small combustion system (boiler) has been installed for use in laboratory evaluations. This system is currently capable of burning Number Two fuel and Number Two emulsions.

Projected developments include the design modification of this laboratory capability in order to burn emulsions of all oil grades. To accomplish this goal it will be necessary to design a nozzle and ignition system to function within this laboratory system. It is anticipated that within three months that furnace will burn emulsions of Number Four fuel oil. It will take an additional nine months to combust Number Six fuel emulsions as a result of the requirements to heat Number Six oil.

At the same time projected activities in the diesel engine emulsification system will concentrate on simplification of the system and improvement of the peripheral equipment reliability. The diesel engine test bed facility is being modified to incorporate some of the system simplification which have come to the forefront as this research program was concluded. Test procedures and equipment are being modified to increase reliability and the accuracy with which this equipment functions. Additional diesel engine tests are anticipated in order to evaluate the facility modifications.

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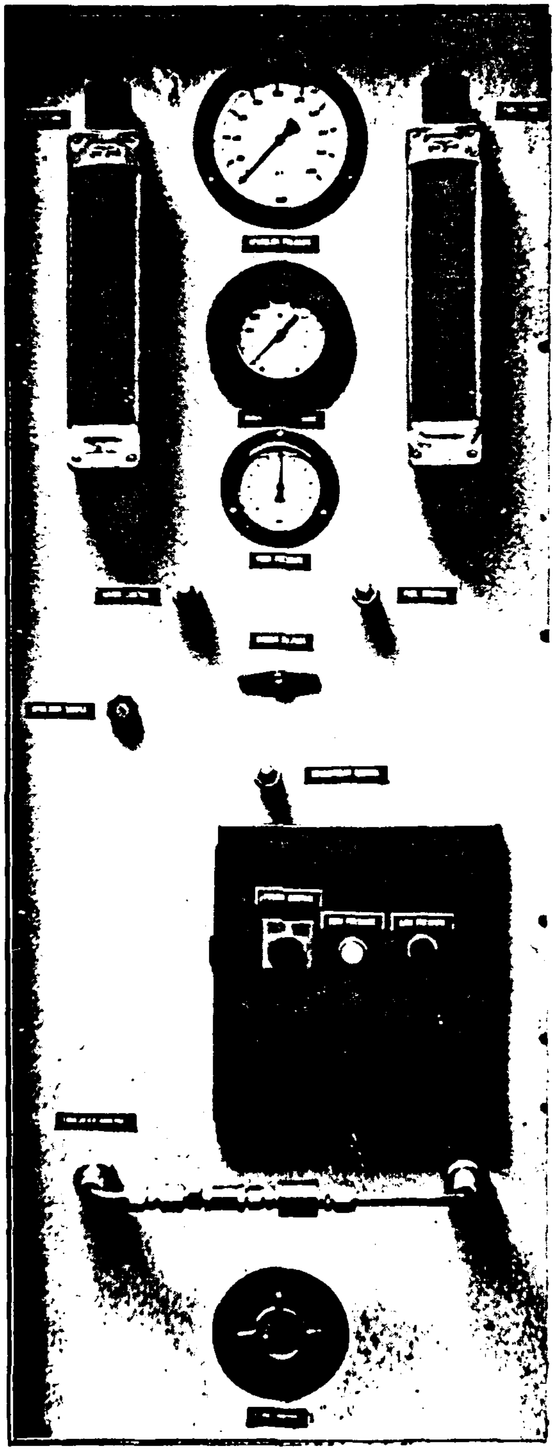


FIGURE 1 PHOTOGRAPH OF THE DAI EMULSIFICATION FACILITY APPARATUS USED IN THE INITIAL STABILITY AND COMBUSTION FEASIBILITY STUDIES

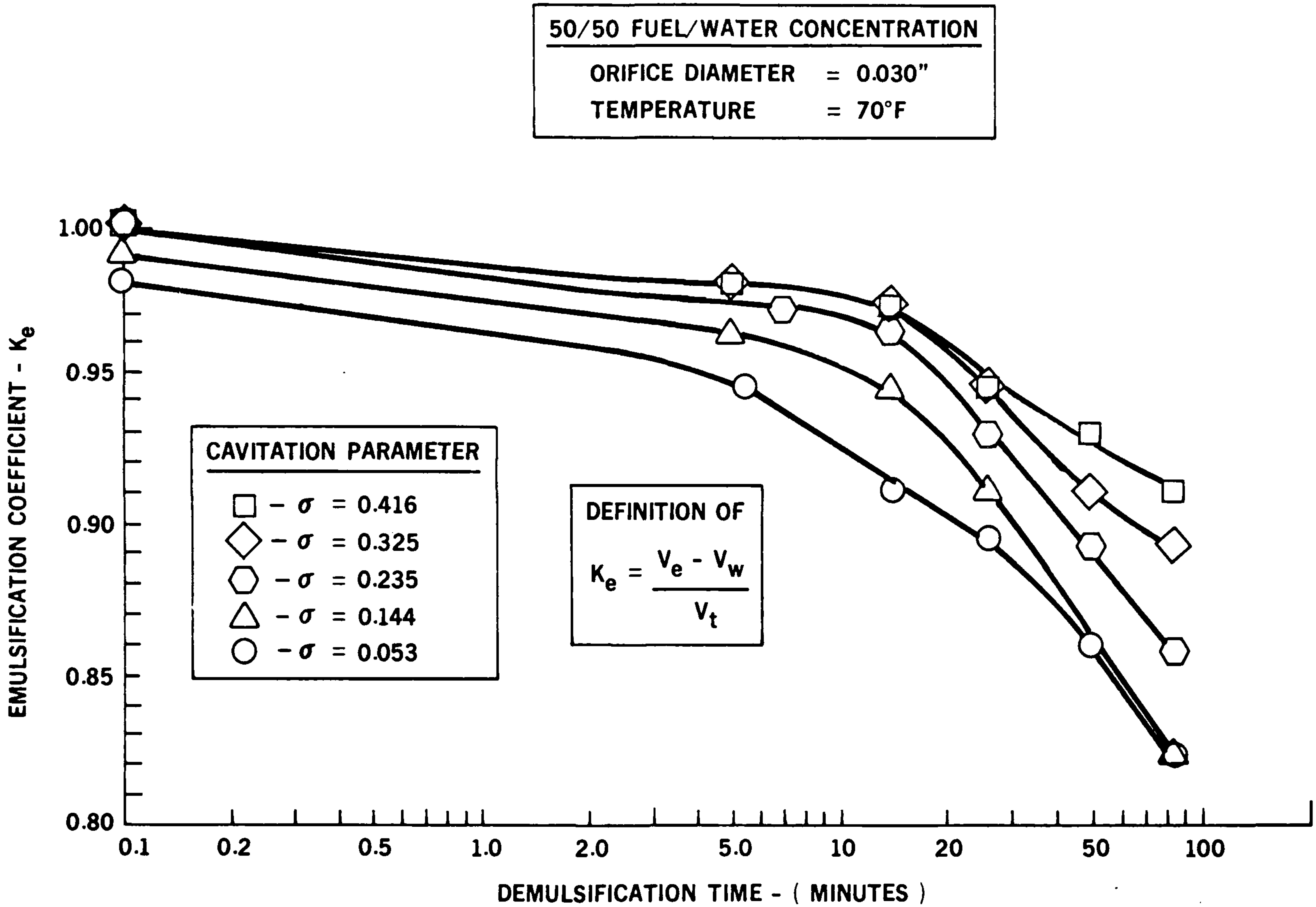


FIGURE 2 RELATIONSHIP OF EMULSIBILITY COEFFICIENT TO DEMULSIFICATION TIME WITH RESPECT TO THE CAVITATION PARAMETER (σ) FOR A 0.030 INCH DIAMETER EMULSIFIER ORIFICE AND A 50/50 FUEL/WATER CONCENTRATION

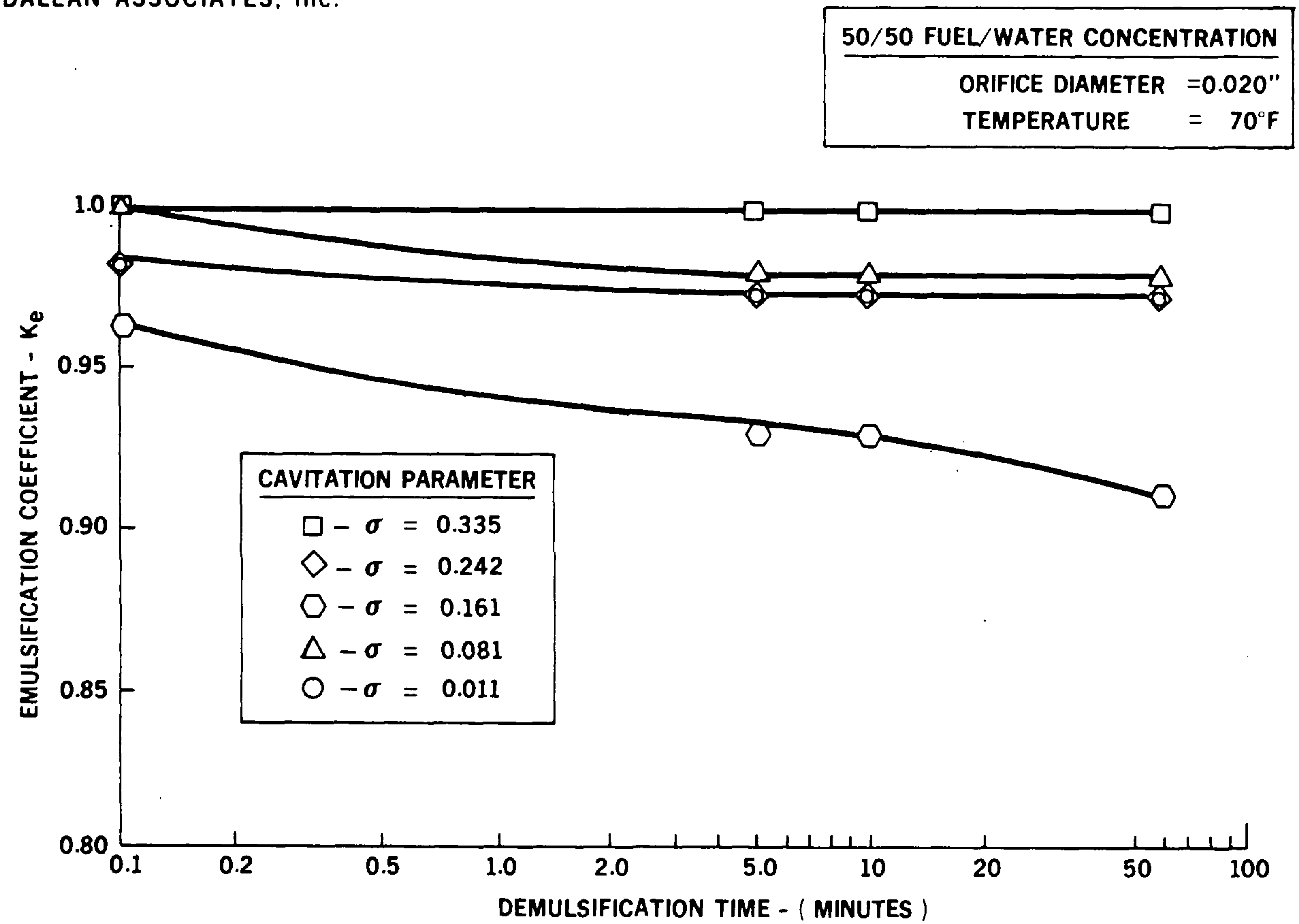


FIGURE 3 RELATIONSHIP OF EMULSIBILITY TO DEMULSIFICATION TIME WITH RESPECT TO CAVITATION PARAMETER (σ) FOR A 0.020 INCH DIAMETER EMULSIFIER ORIFICE AND A 50/50 FUEL/WATER CONCENTRATION

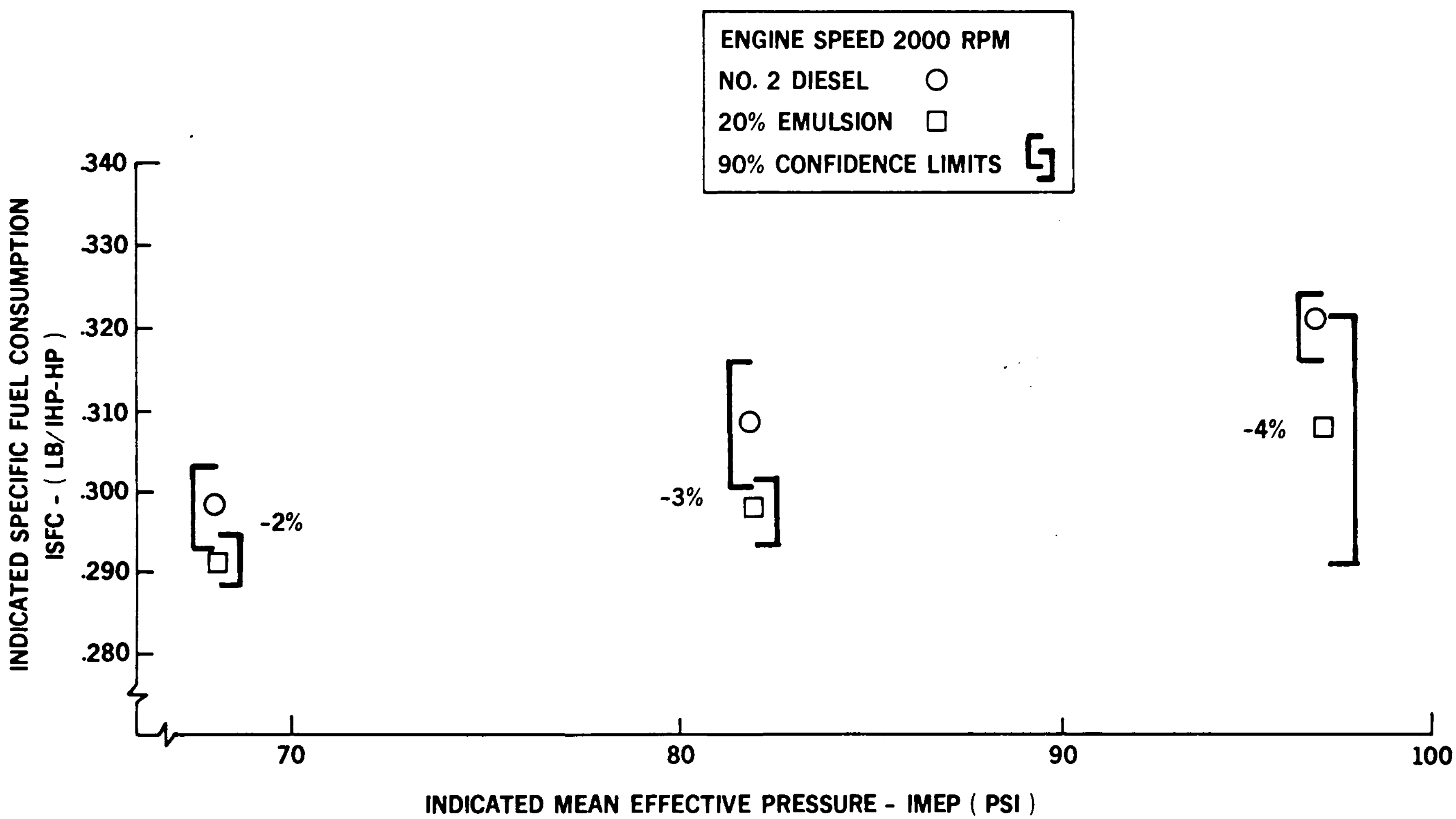


FIGURE 4 SPECIFIC FUEL CONSUMPTION TEST DATA FOR SINGLE CYLINDER DIESEL ENGINE OPERATION

DAEDALEAN ASSOCIATES, Inc.

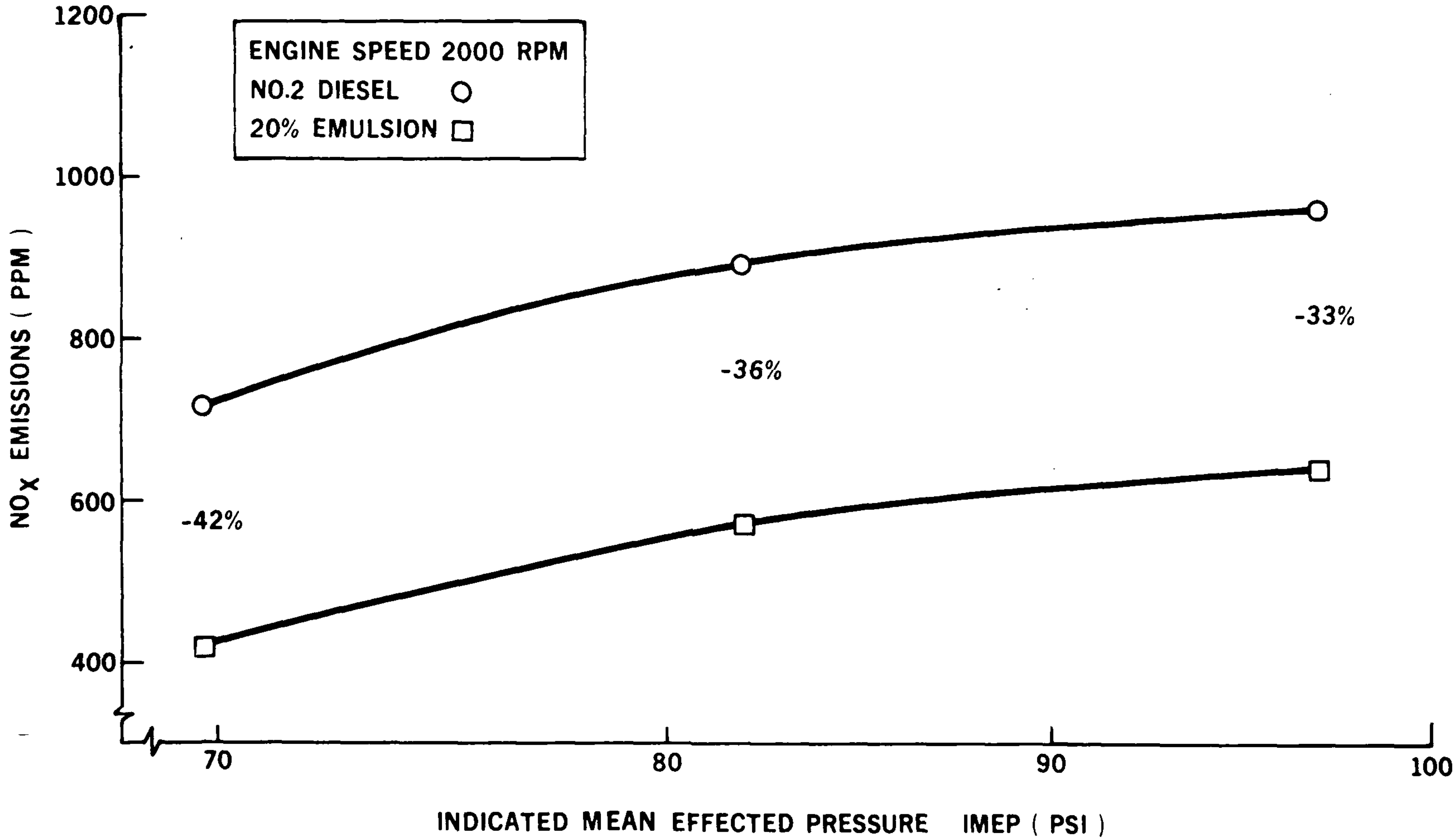


FIGURE 5 NITROGEN OXIDE COMPOUNDS EMISSIONS TEST DATA FOR SINGLE CYLINDER DIESEL ENGINE OPERATION

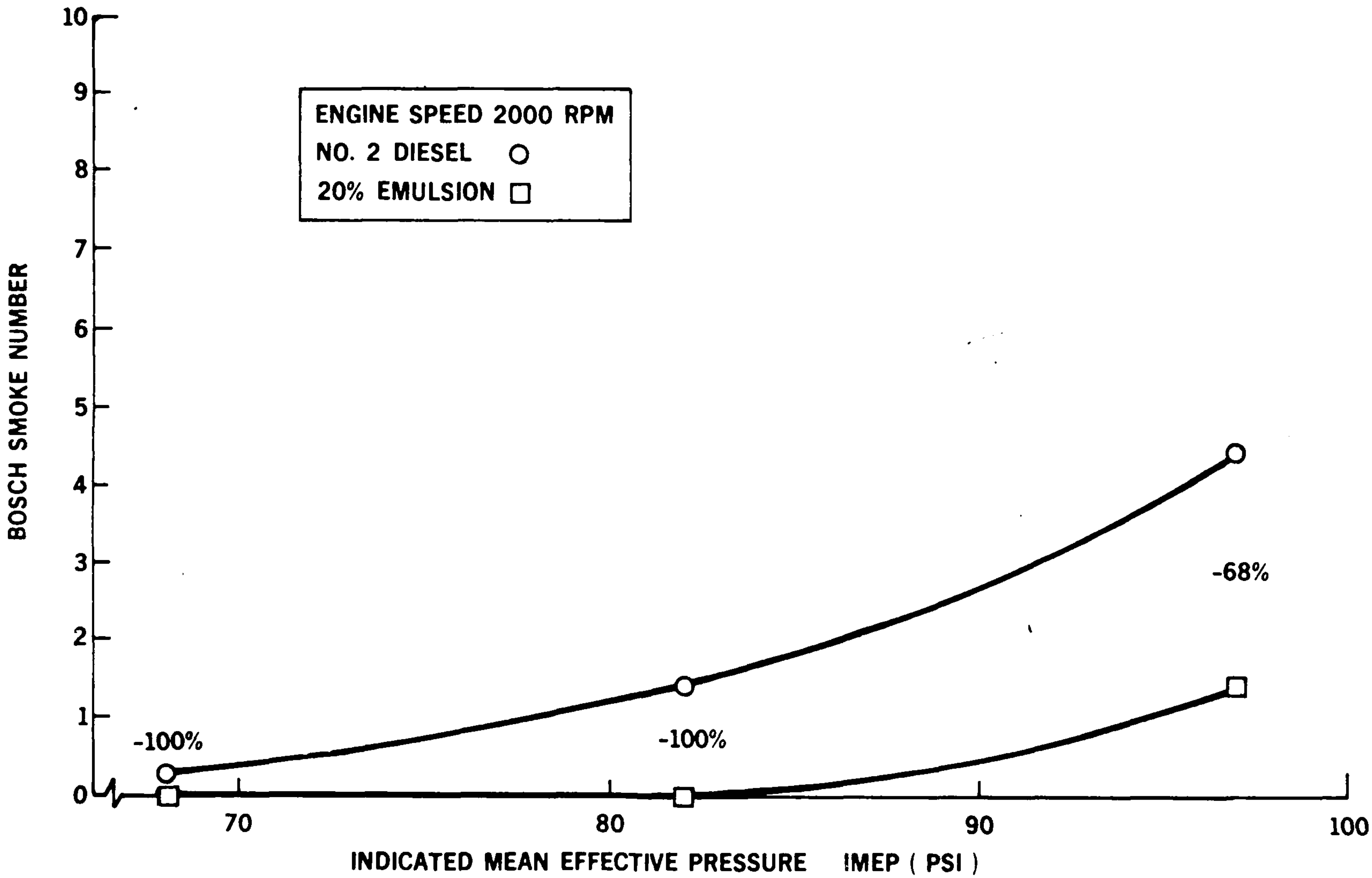


FIGURE 6 BOSCH SMOKE TEST DATA FOR SINGLE CYLINDER DIESEL ENGINE OPERATION

DAEDALEAN ASSOCIATES, Inc.

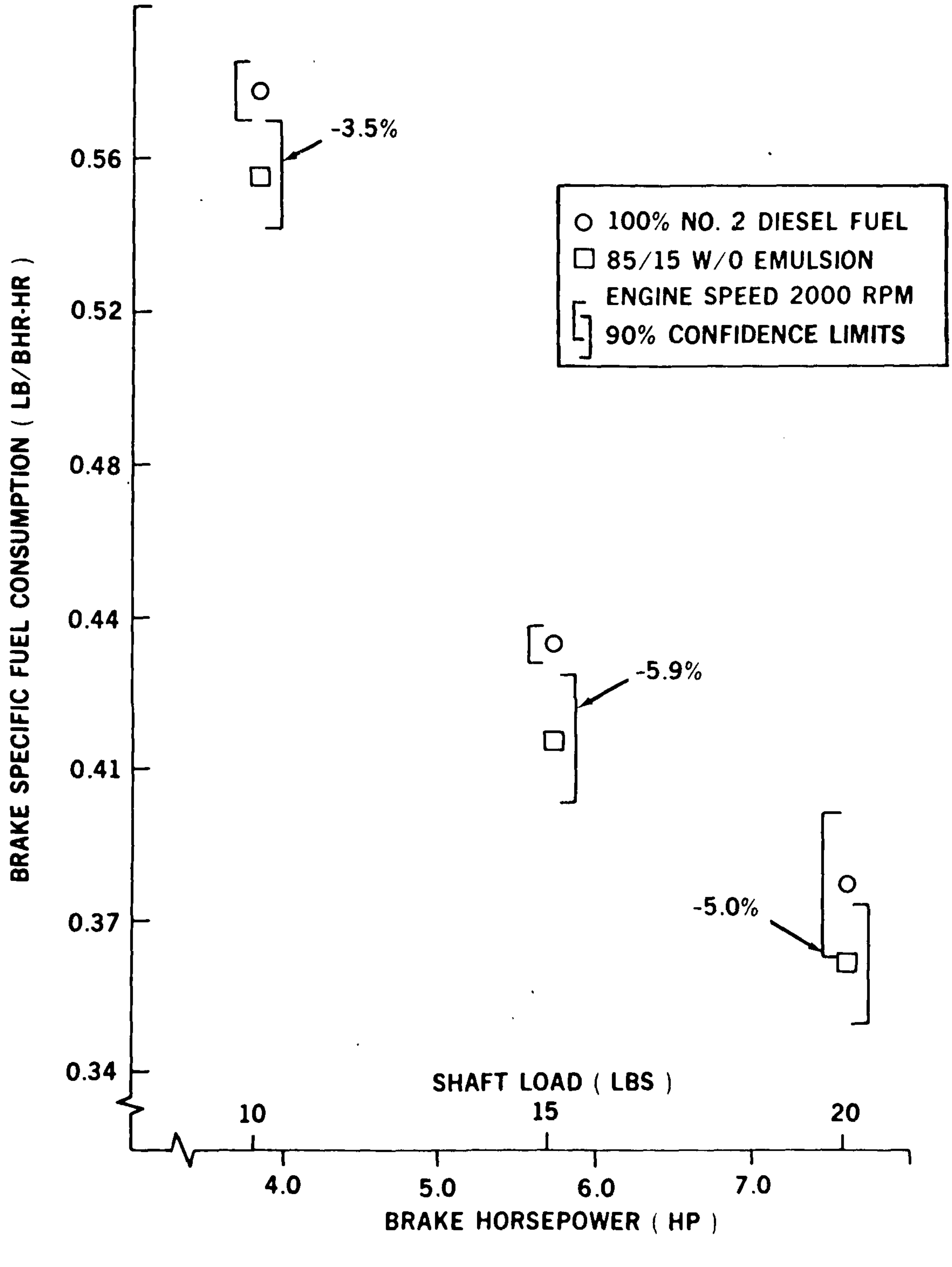
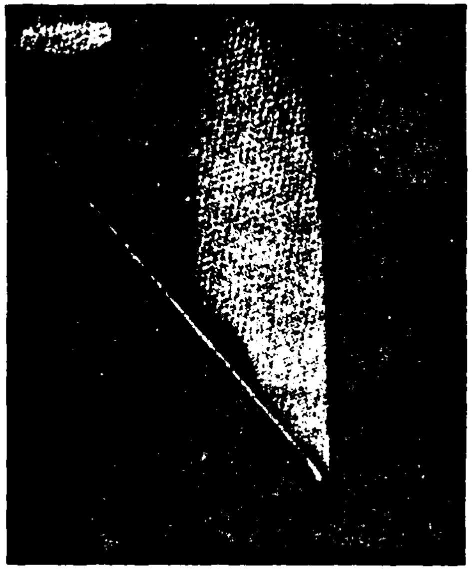
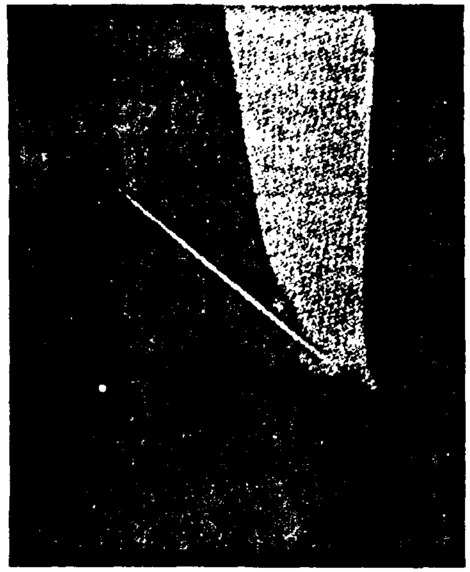


FIGURE 7 PERFORMANCE DATA OF A TWO CYLINDER 12 HP DIESEL ENGINE SHOWING IMPROVEMENTS IN FUEL ECONOMY THROUGH A REDUCTION IN BRAKE SPECIFIC FUEL CONSUMPTION WHEN UTILIZING THE DAI ON-LINE EMULSIFICATION DEVICE



COMBUSTION OF A PURE OIL DROP

- THE PURE OIL DROP BURNS IN THE USUAL WAY WITH NO DISRUPTION



BURNING WATER/OIL EMULSION DROP WITH 10 PERCENT SURFACTANT

- 10 PERCENT SURFACTANT
- NO MINI-EXPLOSION OCCURS

WATER/OIL EMULSION DROP WITH NO SURFACTANT UNDERGOING MINI-EXPLOSION

- NO SURFACTANT USED
- THE EMULSION DROP EXPLODES VIOLENTLY INTO MANY SMALL (APPROX. 1 MICRON) HIGH-VELOCITY FRAGMENTS
- BURNING TIMES OF EMULSION DROPS ARE REDUCED AT LEAST 50 PERCENT

SOURCE: ADELPHI UNIVERSITY
CENTER FOR ENERGY STUDIES
GARDEN CITY, NEW YORK

FIGURE 8 HIGH SPEED PHOTOGRAPHS OF OIL AND WATER-IN-OIL EMULSION SINGLE DROPLET COMBUSTION

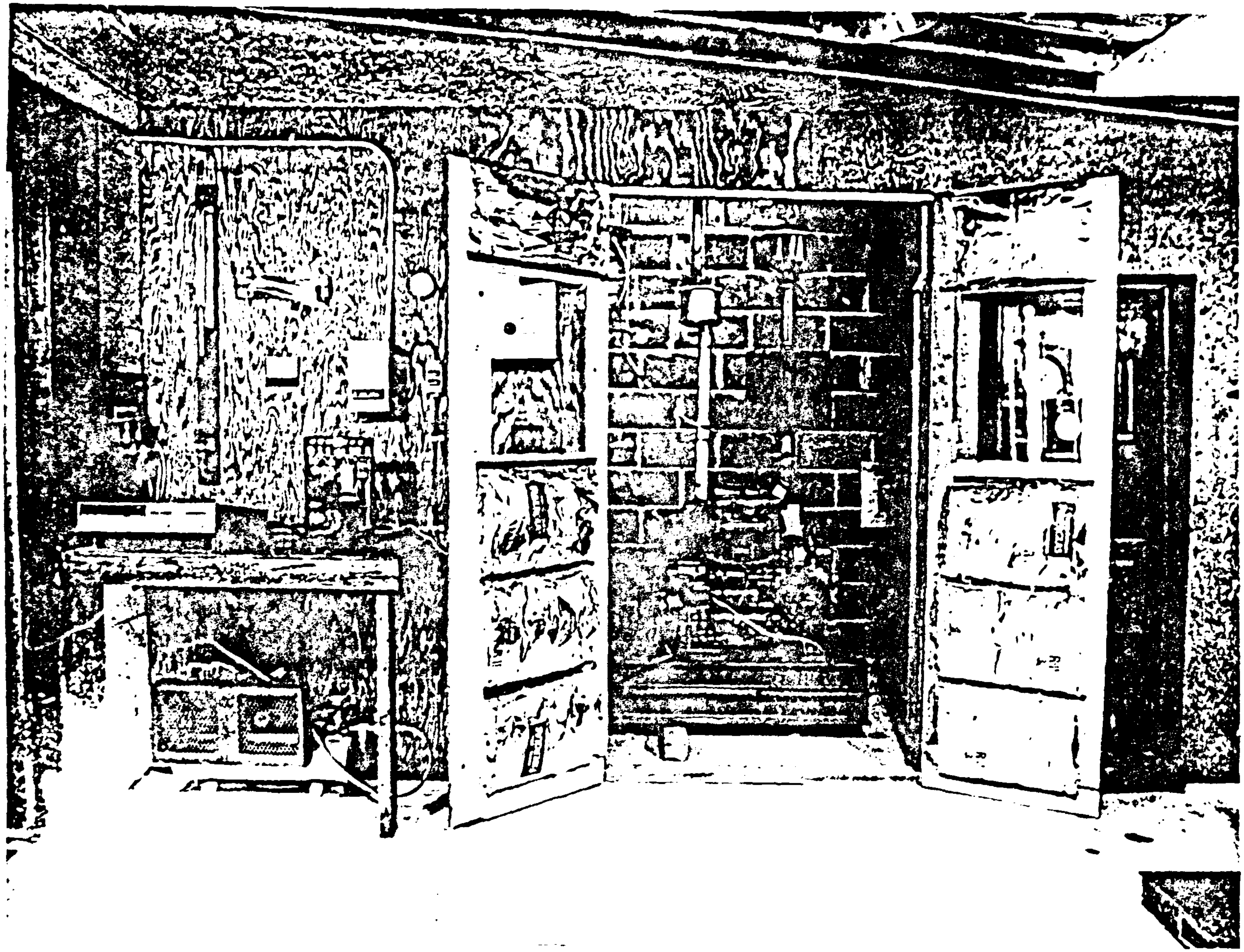


FIGURE 9 PHOTOGRAPHIC OVERVIEW OF DIESEL ENGINE TEST CELL USED TO EVALUATE THE ENERSEC EMULSIFICATION SYSTEM

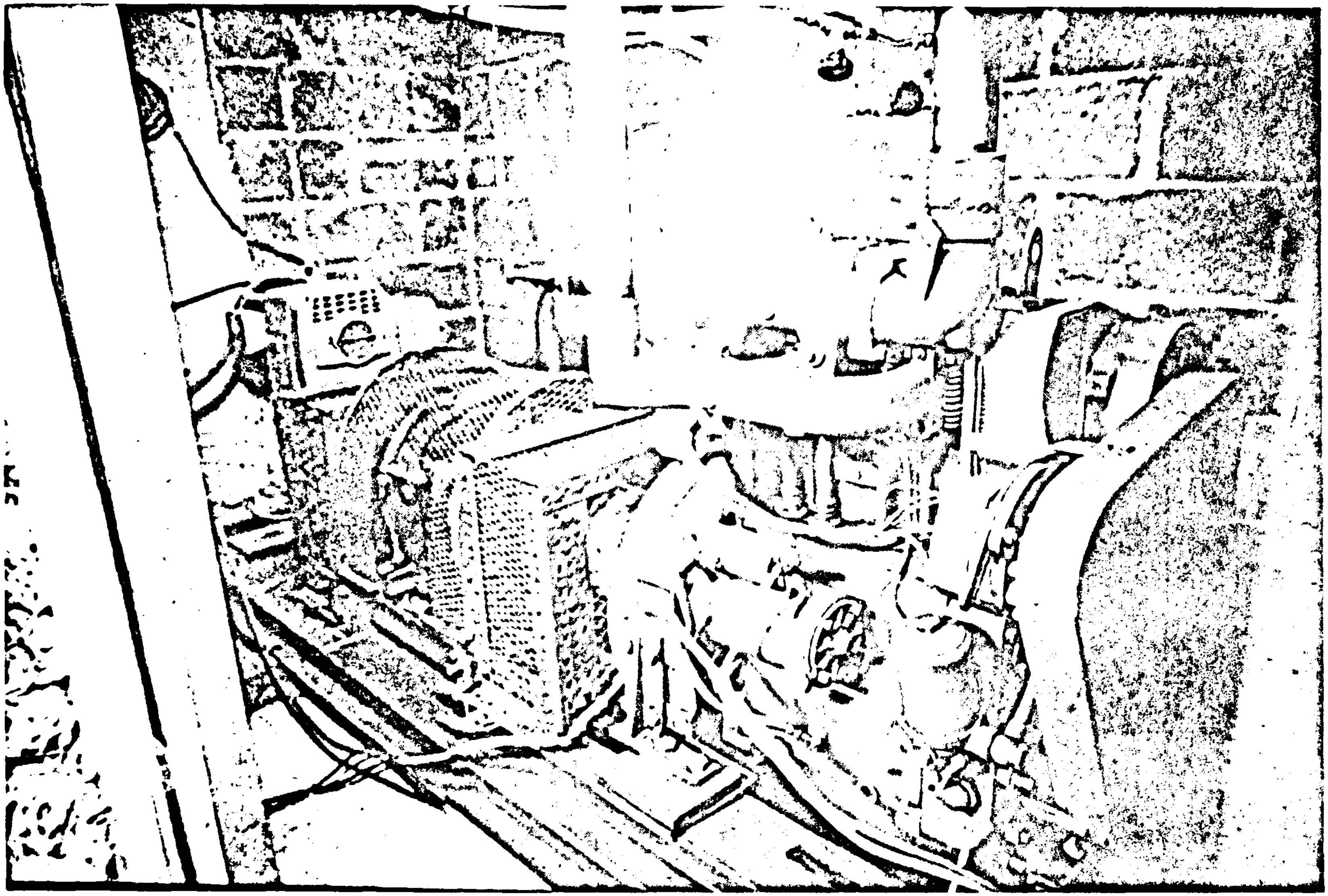


FIGURE 10 CLOSE UP OF THE ENGINE BAY SHOWING THE DIESEL ENGINE, THE DYNAMOMETER AND THE VARIDRIVE SYSTEMS

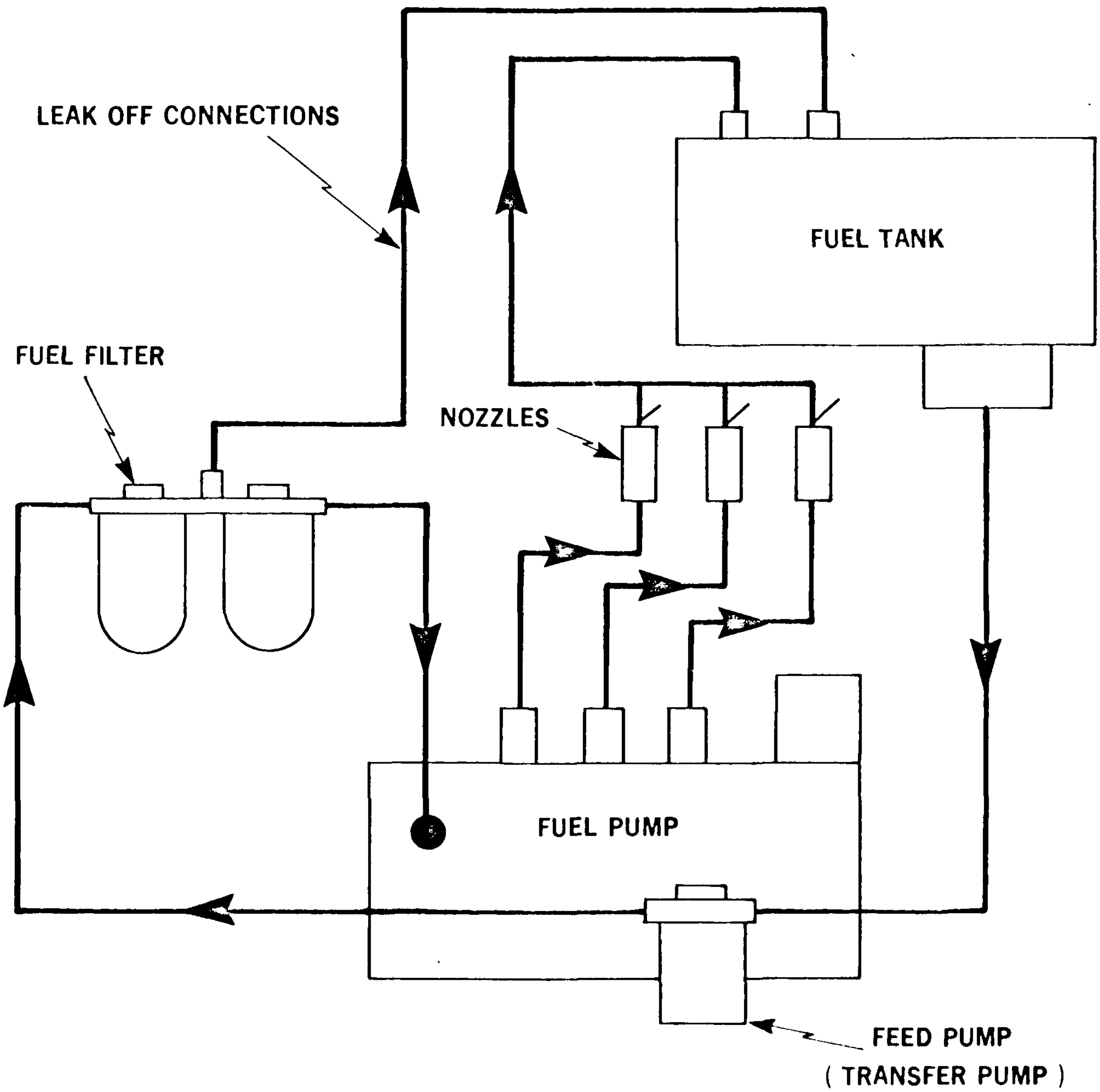


FIGURE 11 THE SCHEMATIC DIAGRAM OF THE FUEL FLOW SYSTEM FOR THE LABORATORY DIESEL ENGINE

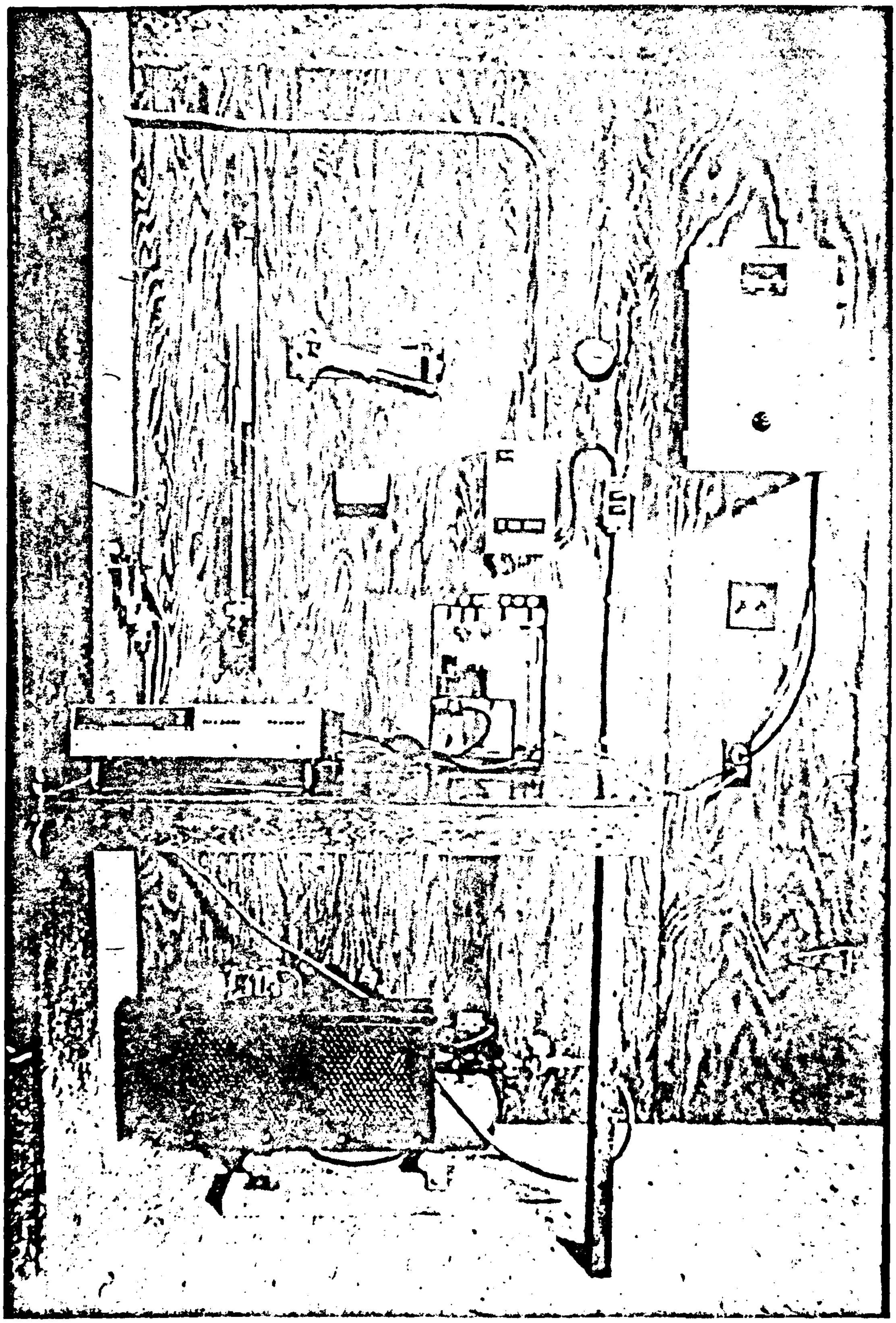


FIGURE 12 CLOSE UP OF THE DATA ACQUISITION SYSTEM USED FOR THE EVALUATION OF EMULSIFIED FUEL IN DIESEL ENGINE TEST DATA COLLECTION

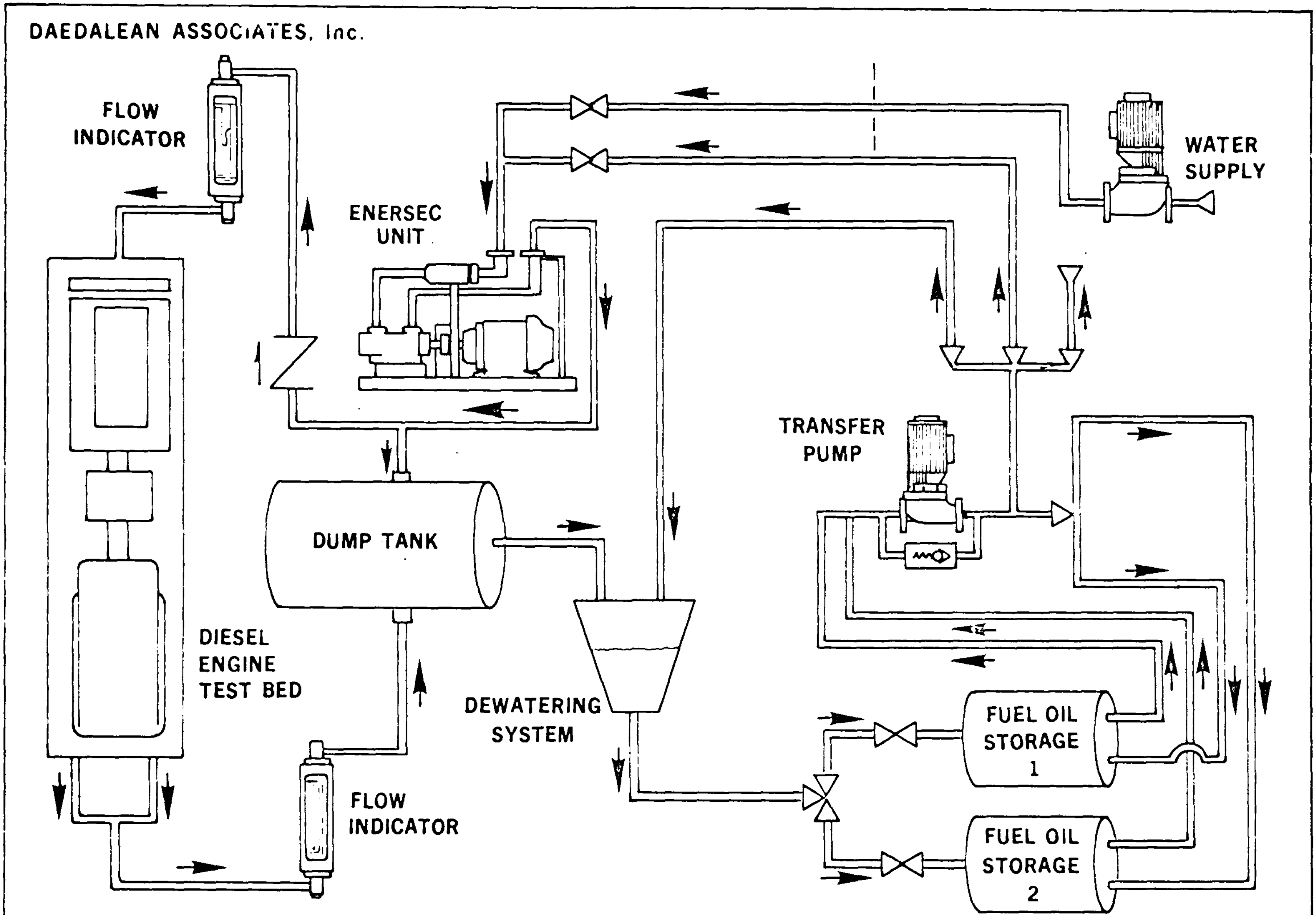


FIGURE 13 SCHEMATIC DIAGRAM OF THE #2 FUEL OIL EMULSIFICATION TEST FACILITY WHICH INCORPORATED FUEL DEWATERING

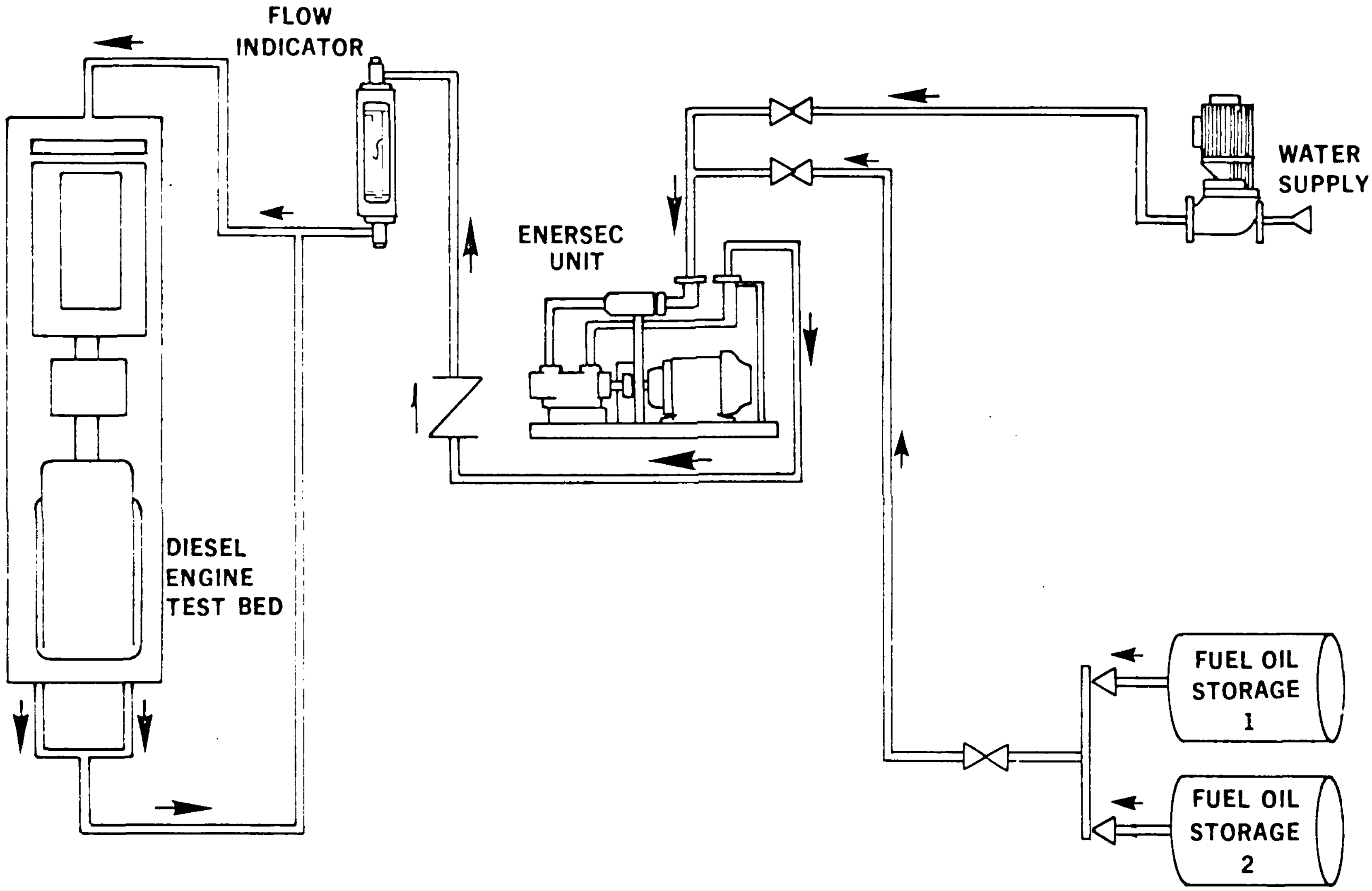


FIGURE 14 SCHEMATIC DIAGRAM OF THE #2 FUEL OIL EMULSIFICATION SYSTEM WITH RECIRCULATION OF DIESEL ENGINE RETURN FLOW

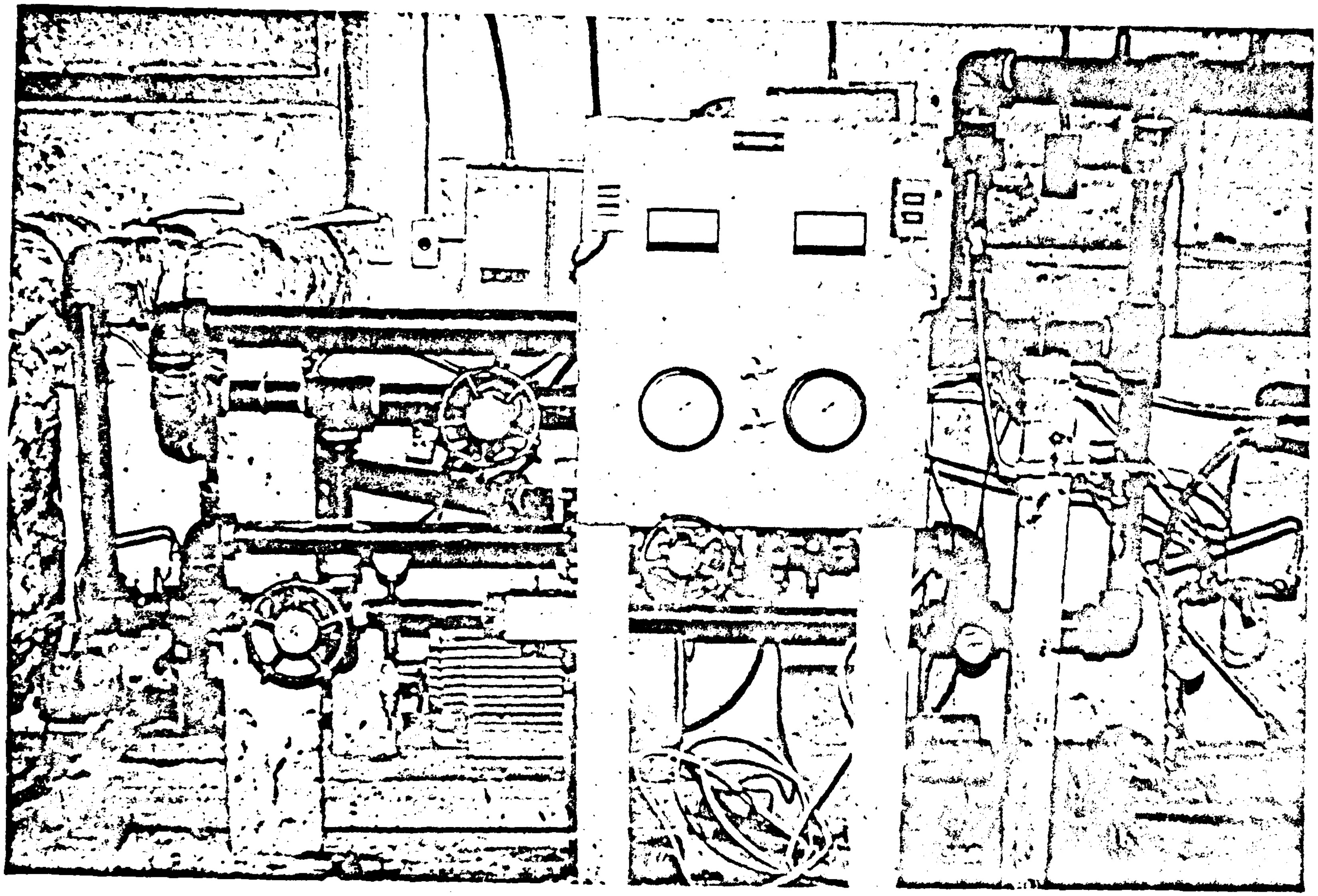


FIGURE 15 PHOTOGRAPH OF NUMBER 6 FUEL OIL TEST LOOP LABORATORY APPARATUS WHICH SIMULATES THE FUEL SUPPLY SYSTEM OF AN INDUSTRIAL BOILER

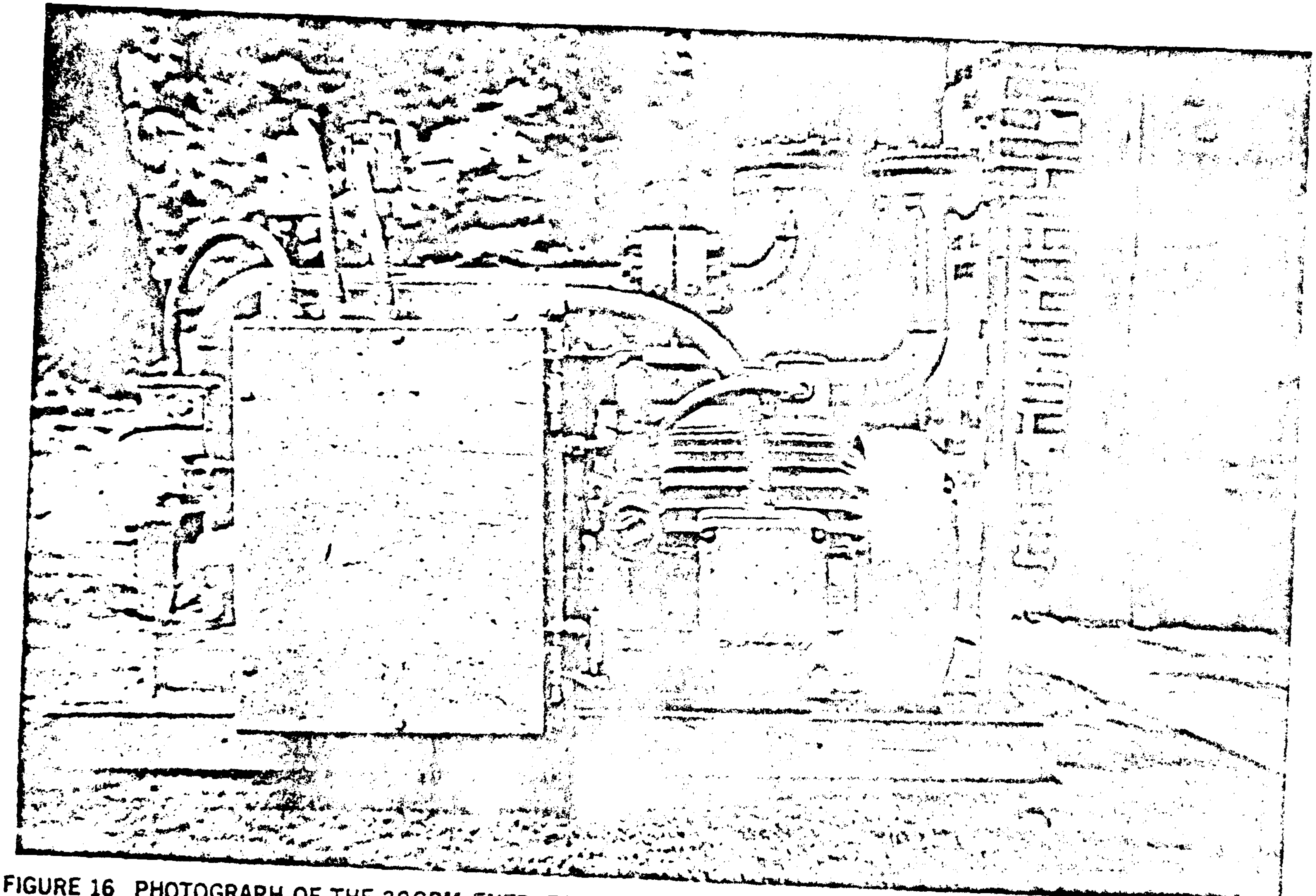
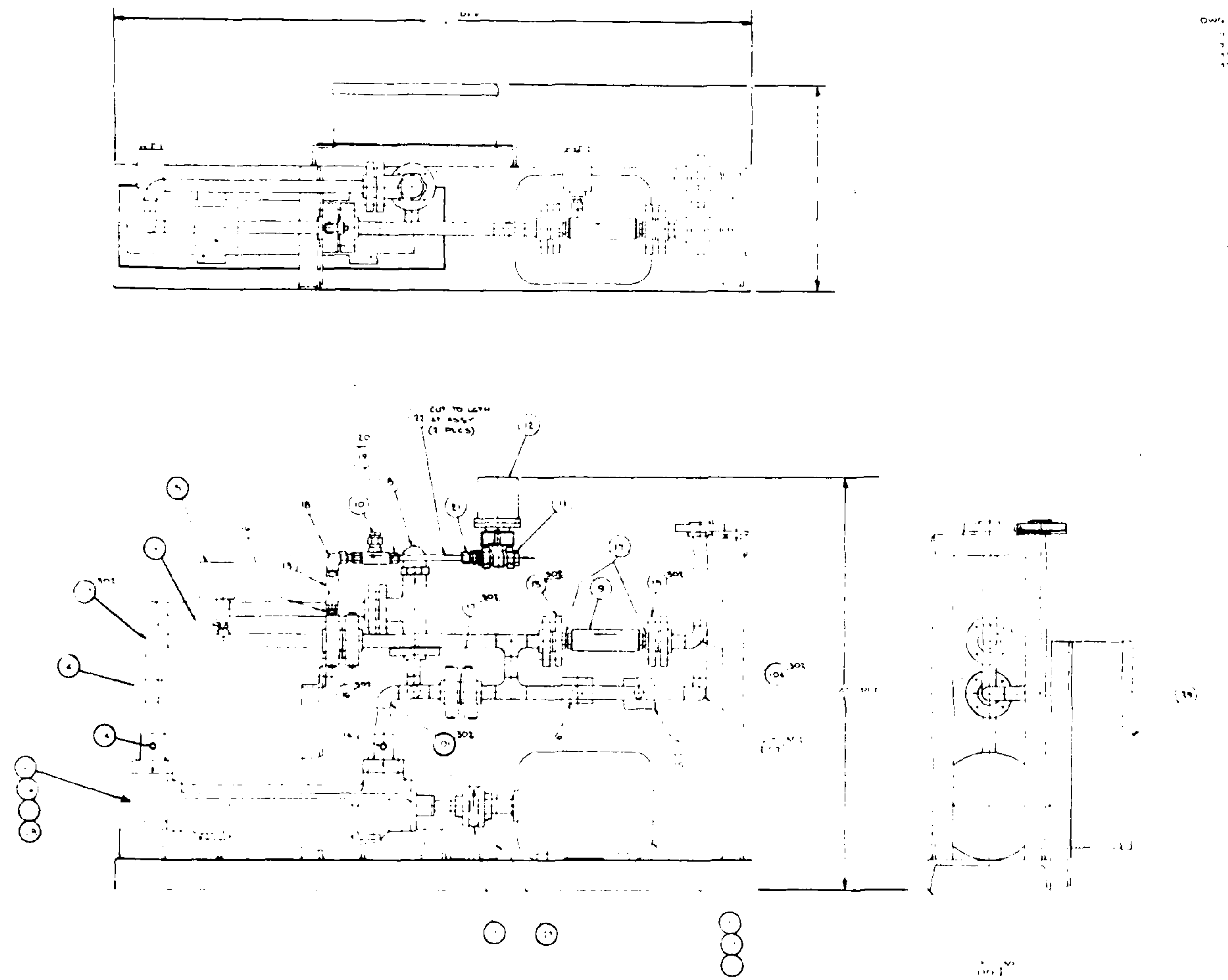


FIGURE 16 PHOTOGRAPH OF THE 30GPM ENERSEC SYSTEM INSTALLED IN BOILER ROOM OF A COMMERCIAL STEAM SHIP TO FEED TWO 100,000 POUNDS STEAM PER HOUR MARINE BOILERS

DAEDALEAN ASSOCIATES, Inc.



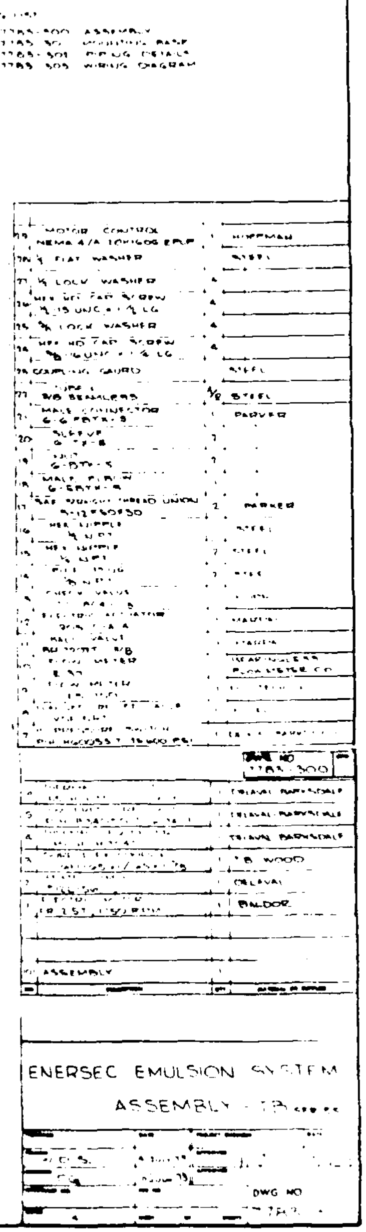


FIGURE 17 ASSEMBLY DRAWING OF VARIABLE FLOW ENERSEC UNIT

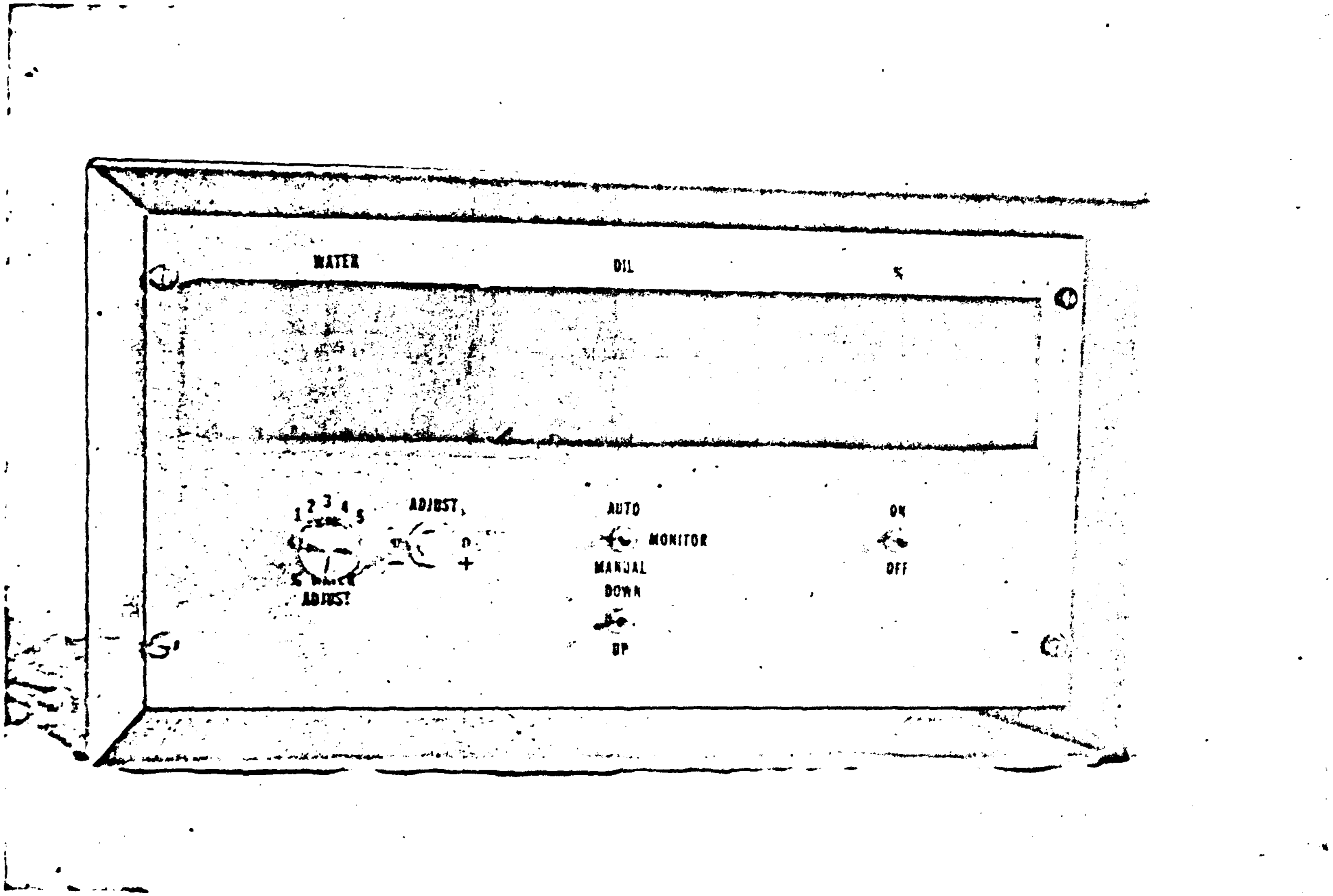


FIGURE 18 THE CONTROL PANEL USED TO MONITOR AND CONTROL THE PERCENTAGE EMULSION PRODUCED IN THE VARIABLE FLOW ENERSEC SYSTEM

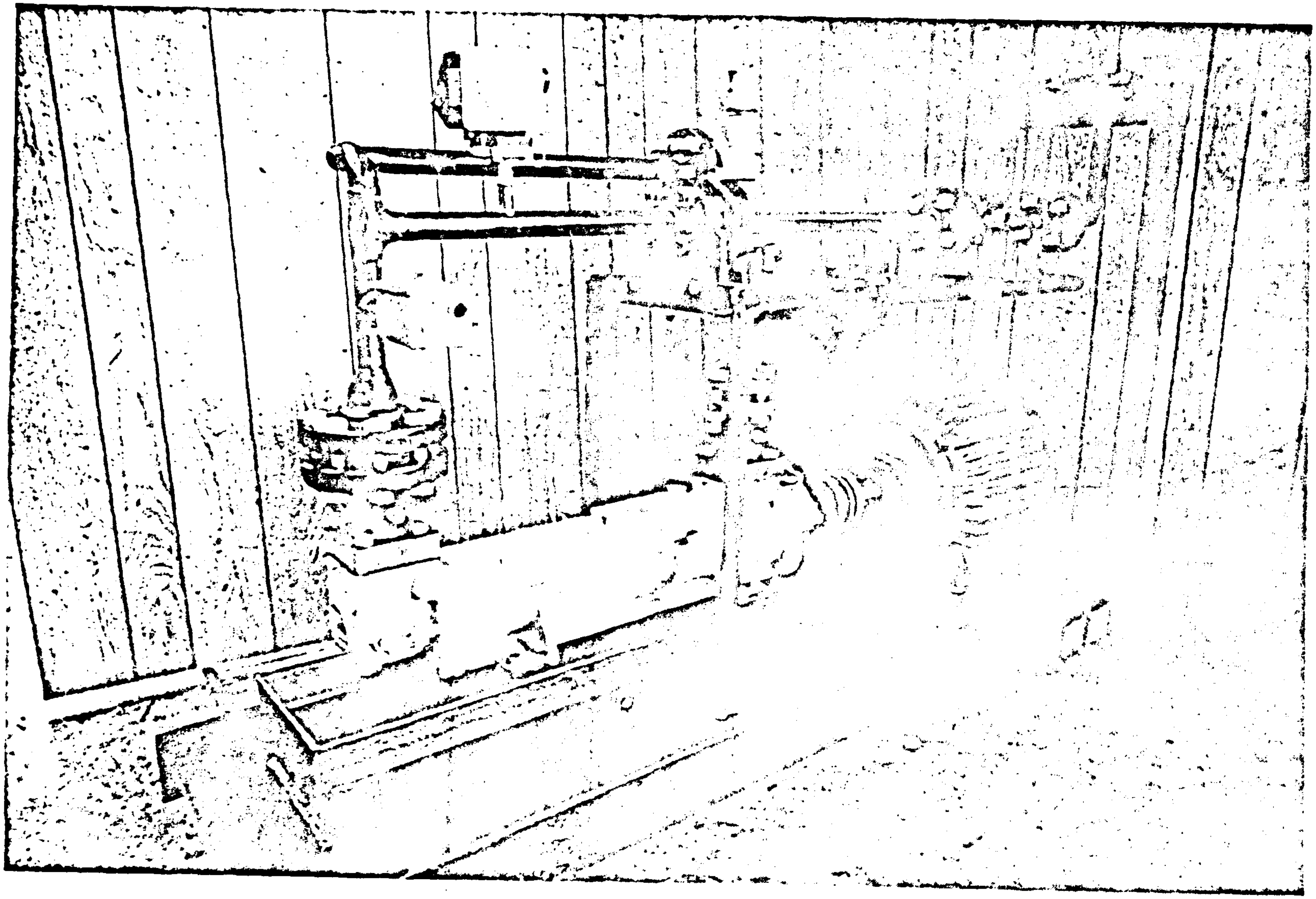


FIGURE 19 PHOTOGRAPH OF THE VARIABLE FLOW RATE SYSTEM AS IT WAS COMPLETED AND READY FOR INSTALLATION IN TEST BOILER

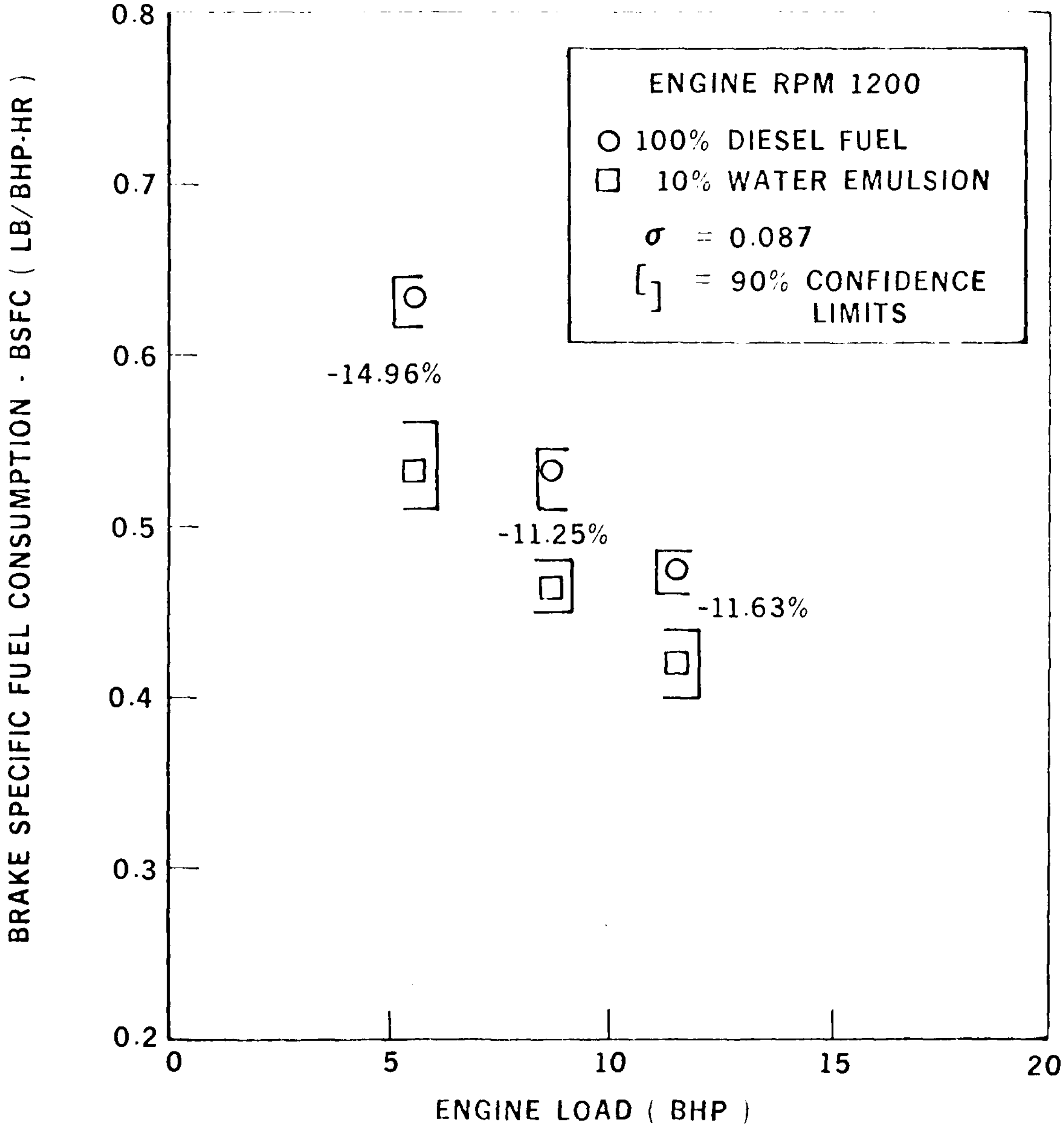


FIGURE 20 SUMMARY GRAPH ILLUSTRATING FUEL CONSUMPTION REDUCTIONS OBTAINED WITH EMULSIFIED FUEL AT AN ENGINE SPEED OF 1200 RPM

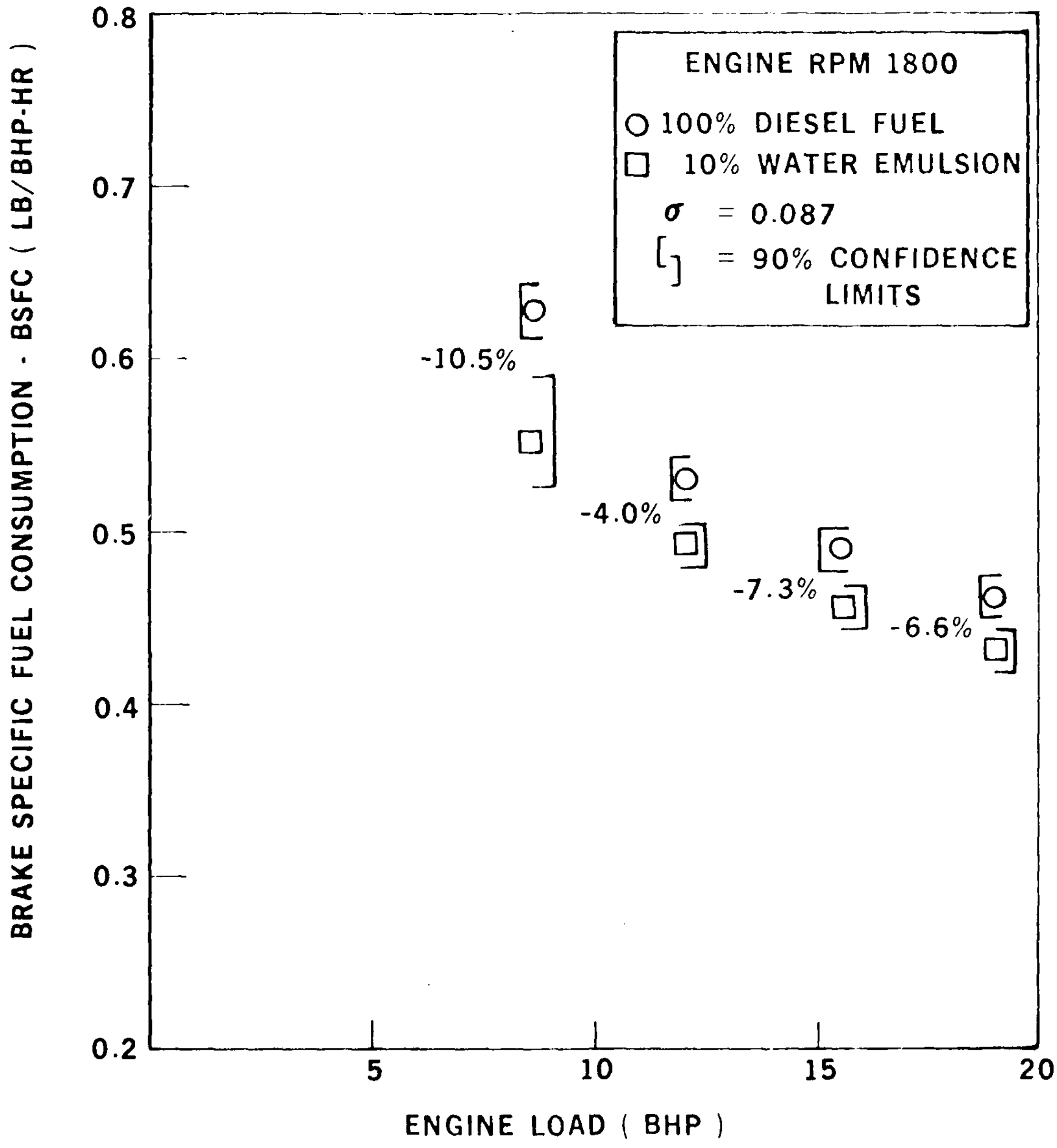


FIGURE 21 SUMMARY GRAPH ILLUSTRATING FUEL CONSUMPTION REDUCTIONS OBTAINED WITH EMULSIFIED FUEL AT AN ENGINE SPEED OF 1800 RPM

DAEDALEAN ASSOCIATES, INC.

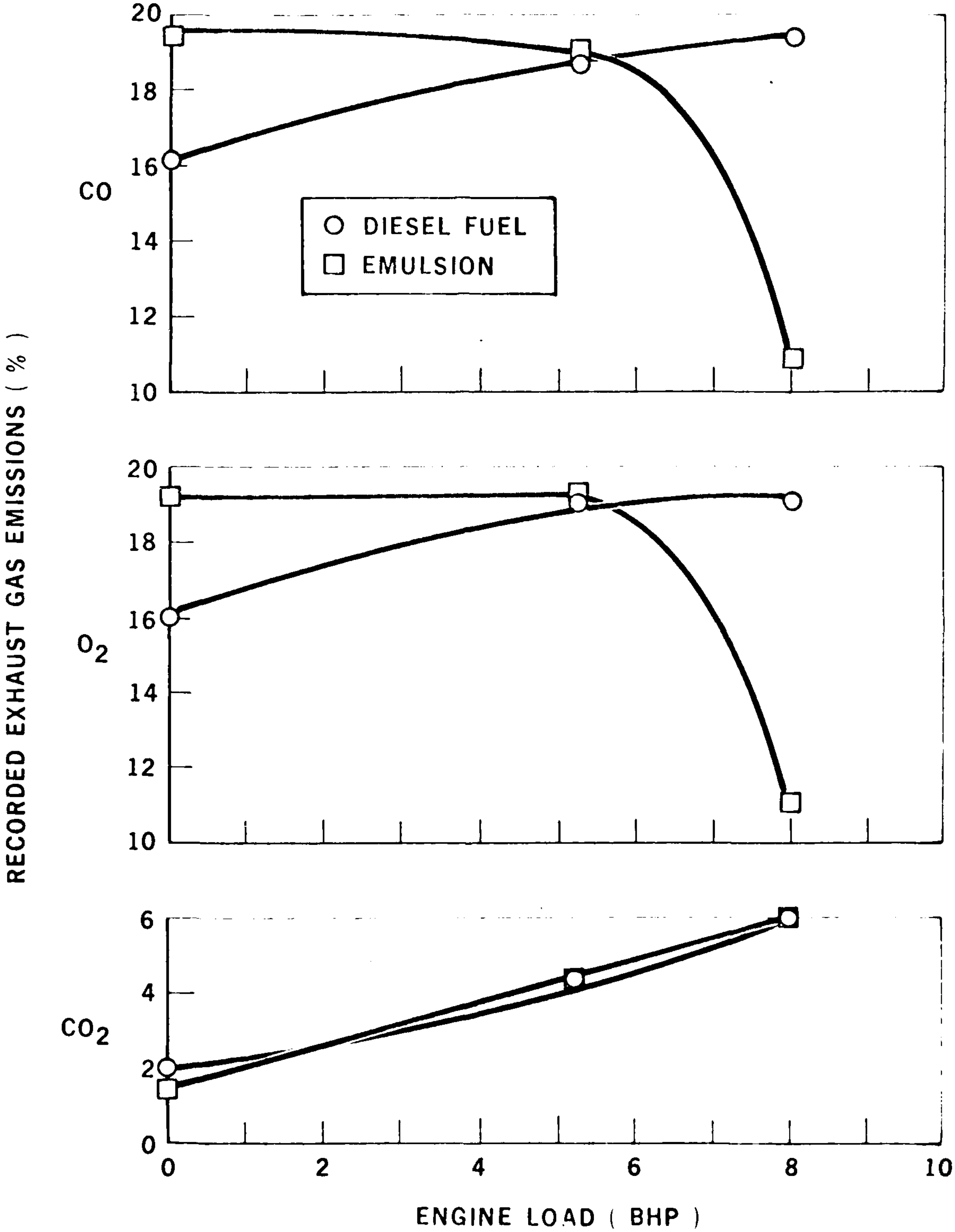
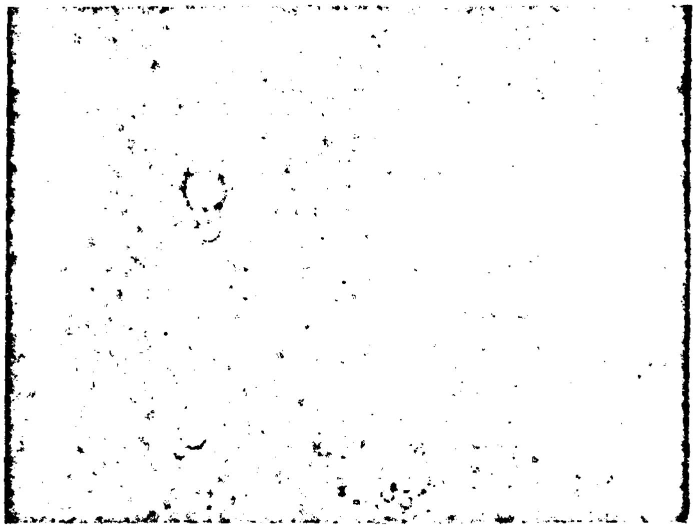
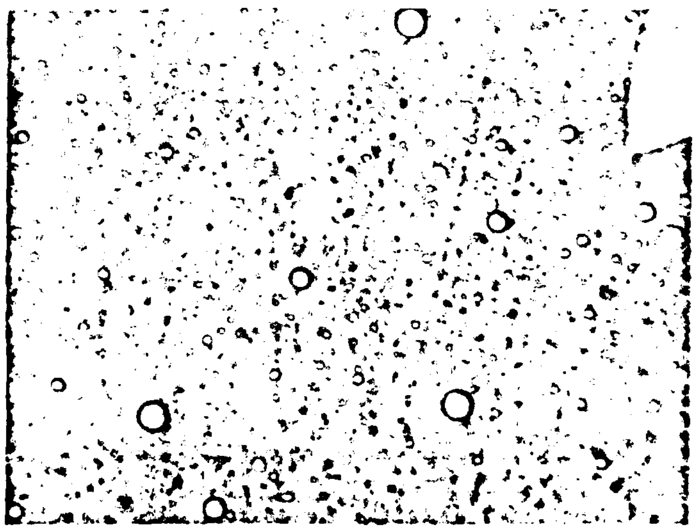


FIGURE 22 SUMMARY DATA OBTAINED FROM THE EXHAUST GAS ANALYSIS AT AN ENGINE SPEED OF 1200 RPM



(SAMPLE A)



(SAMPLE B)

FIGURE 23 PHOTOMICROGRAPHS OF A NO. 6 FUEL OIL AND WATER EMULSION PREPARED JUNE (SAMPLE A) PHOTOGRAPHED AGAIN IN OCTOBER (SAMPLE B). MAGNIFICATION 400 X

EXTRACTION FROM SHIP ENGINE ROOM OPERATING LOG BOOK								
APRIL - PRIOR TO UNIT INSTALLATION								
STARBOARD BOILER SUPERHEATER TEMPERATURE OUTPUT DEGREES F	855	860	861	862	858	858	858	856
PORT BOILER SUPERHEATER TEMPERATURE OUTPUT (DEGREES F)	896	898	895	895	892	896	897	895

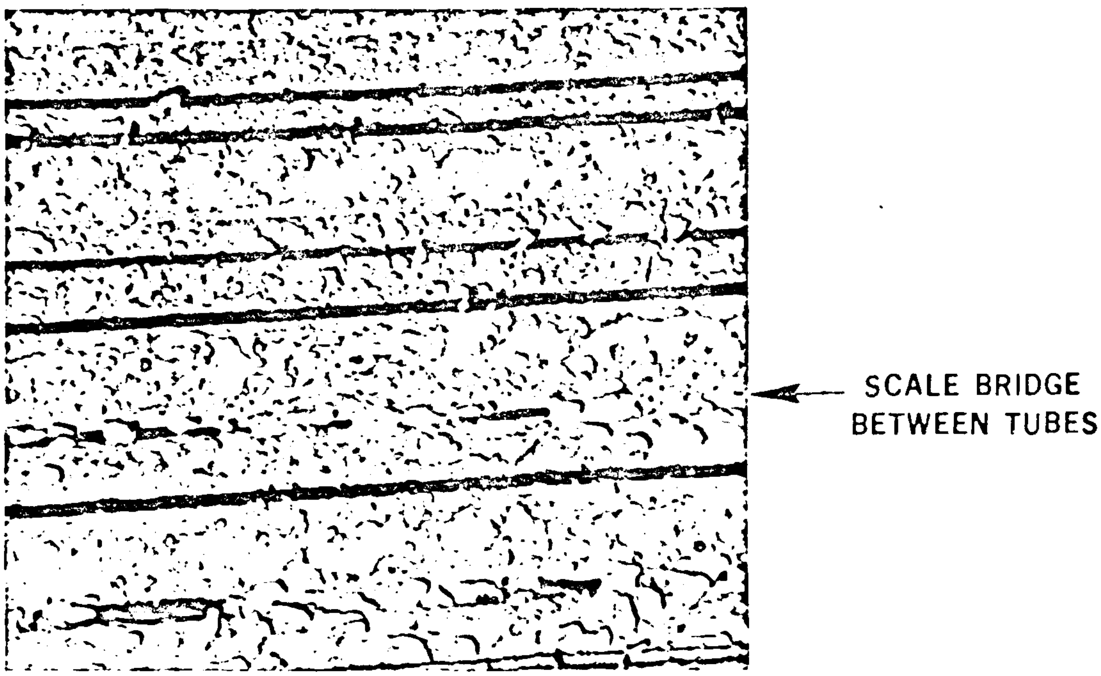
BOILER SUPERHEATER OUTPUT TEMPERATURE RATINGS 950 °F

FIGURE 24 SUPERHEATER OUTPUT TEMPERATURES PRIOR TO EMULSIFIED FUEL USE INDICATING A REDUCTION IN OUTPUT WHICH RESULTS FROM FIRESIDE SCALE FORMATION

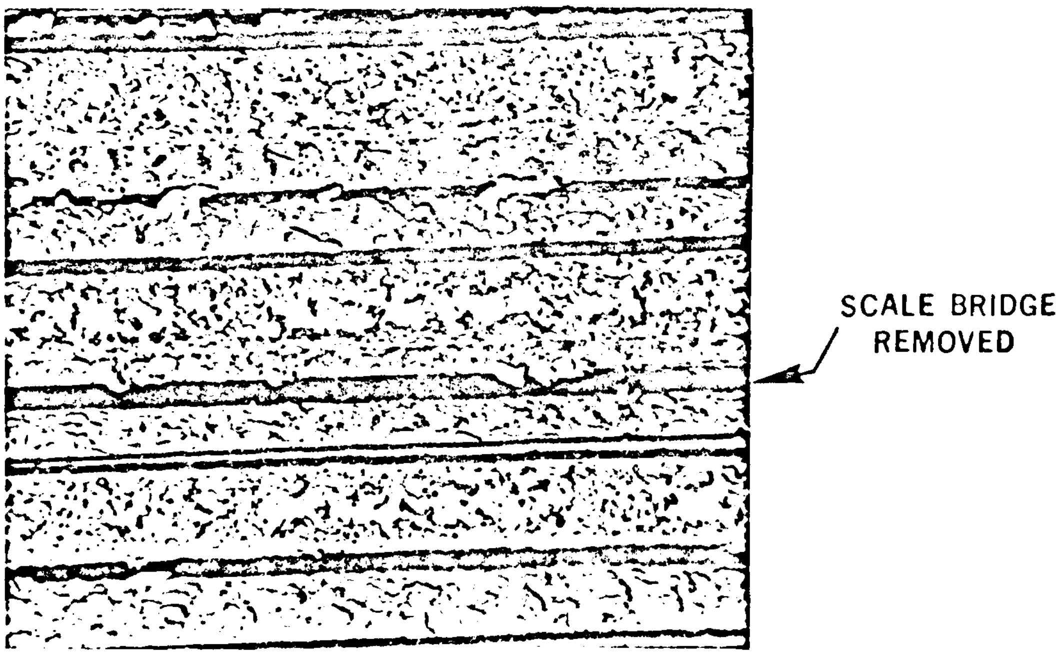
EXTRACTION FROM SHIP ENGINE ROOM OPERATING LOG BOOK								
	AUGUST/SEPTEMBER OPERATING ON EMULSIFIED FUEL							
STARBOARD BOILER SUPERHEATER TEMPERATURE OUTPUT DEGREES F	950	945	952	950	955	955	950	955
PORT BOILER SUPERHEATER TEMPERATURE OUTPUT (DEGREES F)	935	945	940	940	940	942	950	955

BOILER SUPERHEATER OUTPUT TEMPERATURE RATINGS 950° F

FIGURE 25 SUPERHEATER OUTPUT TEMPERATURES AS THE BOILERS OPERATED ON EMULSIFIED FUEL INDICATING THE MAINTENANCE OF RATED TEMPERATURE AND ELIMINATION OF FIRESIDE SCALE



FIRESIDE TUBES AFTER OPERATION WITH #6 FUEL OIL



THE SAME FIRESIDE TUBES AFTER 45 DAY OPERATION WITH WATER IN #6 FUEL OIL EMULSIFIED FUEL

SOURCE: DELTA STEAMSHIP COMPANY

FIGURE 26 PHOTOGRAPHIC EVIDENCE OF THE CLEANING EFFECT ON BOILER FIRESIDE SCALE RESULTING FROM BURNING EMULSIFIED FUELS

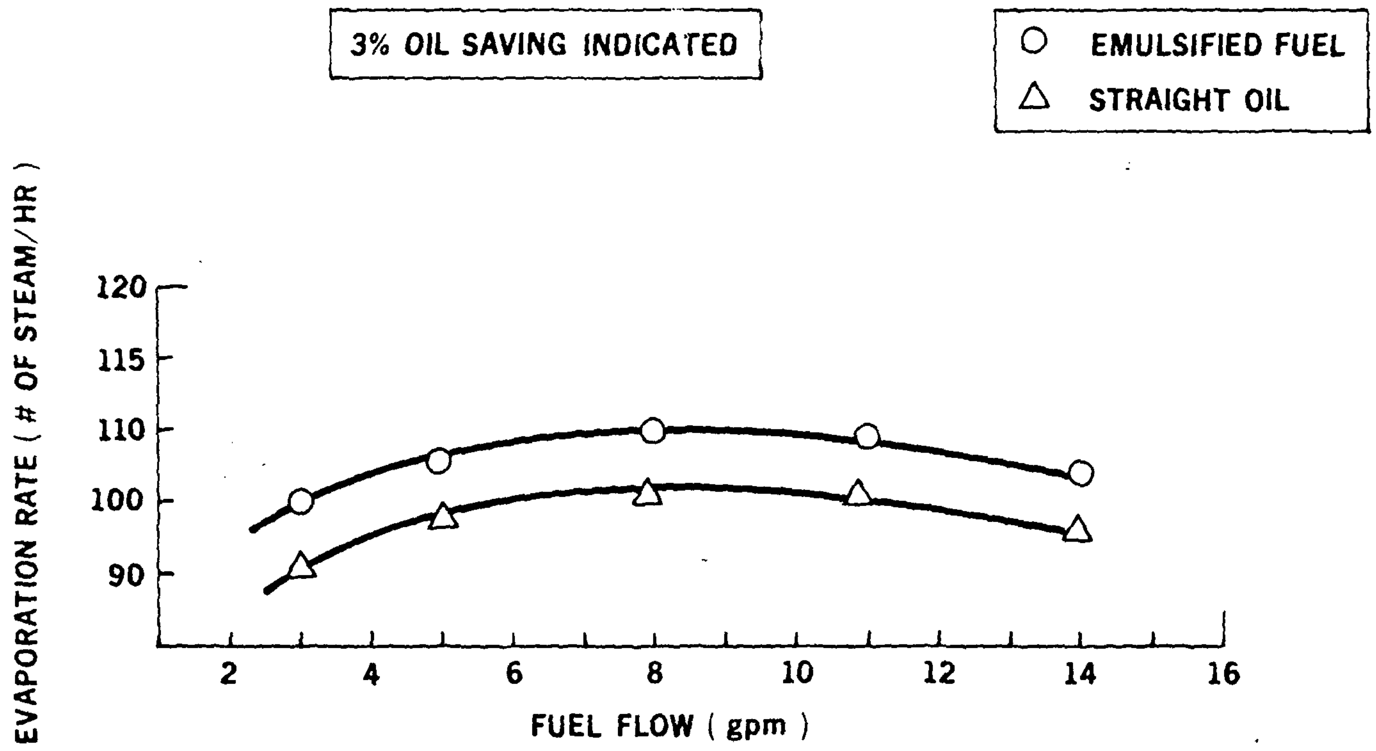


FIGURE 27 DATA OBTAINED FROM GEORGIA PACIFIC ENERSEC INSTALLATION INDICATING 3% APPROXIMATE FUEL REDUCTION USING EMULSIFIED FUEL

SOURCE : GEORGIA PACIFIC

FIGURE 28 PHOTOGRAPH OF THE CLEANING OF THE FIRESIDE AFTER USING EMULSIFIED FUEL IN THE BOILER

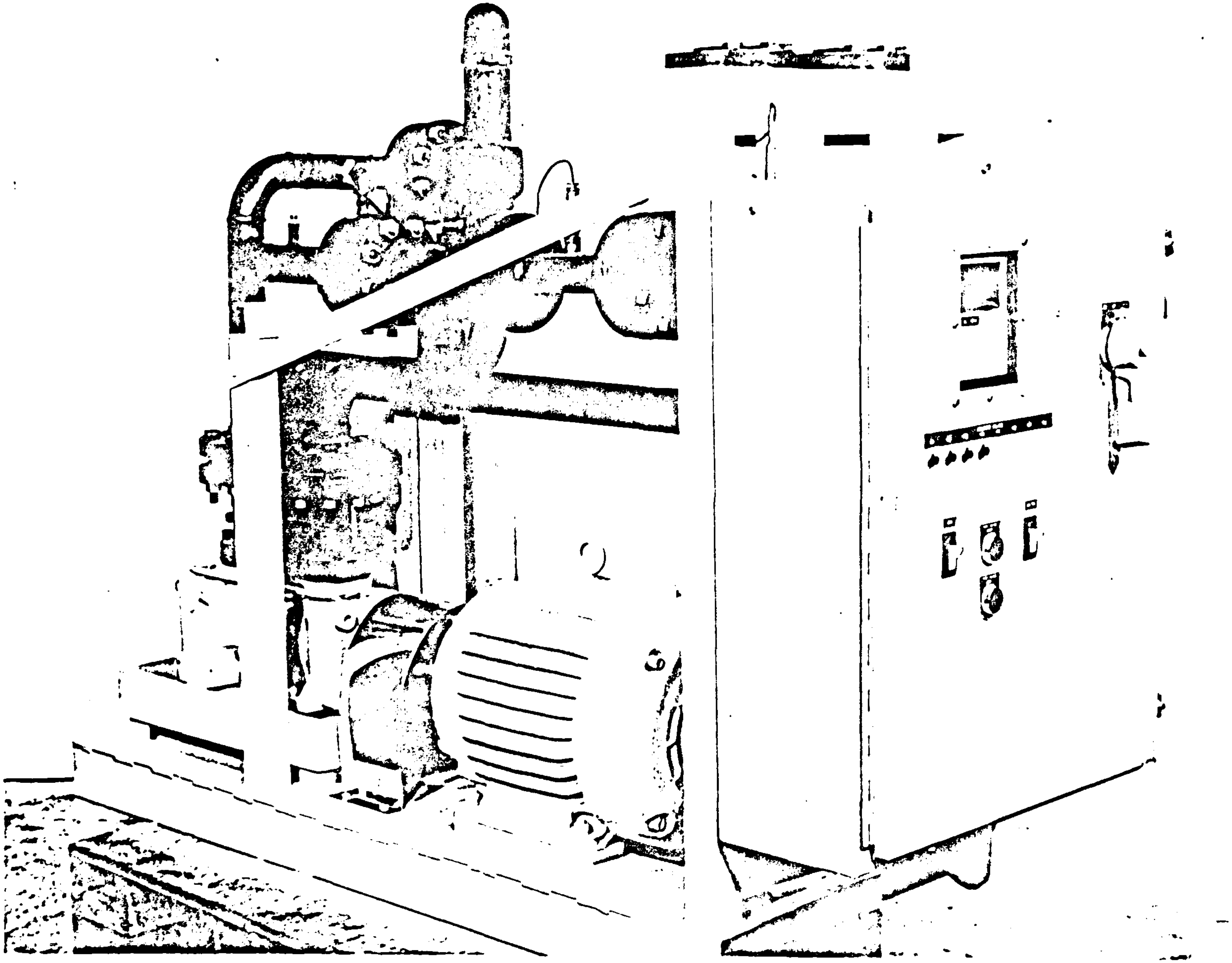
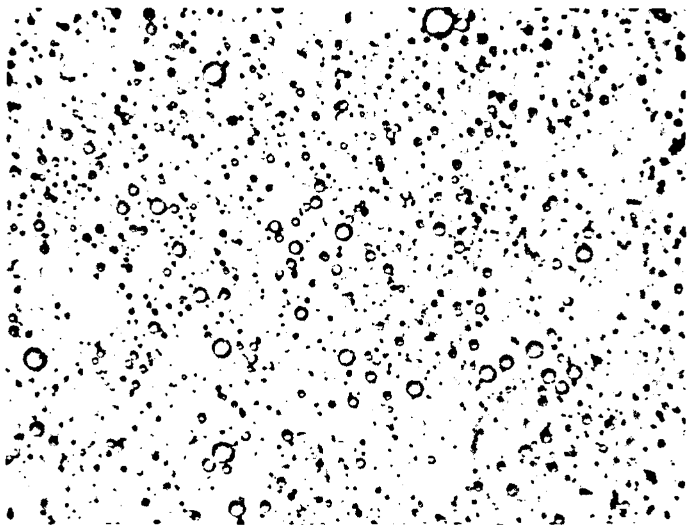
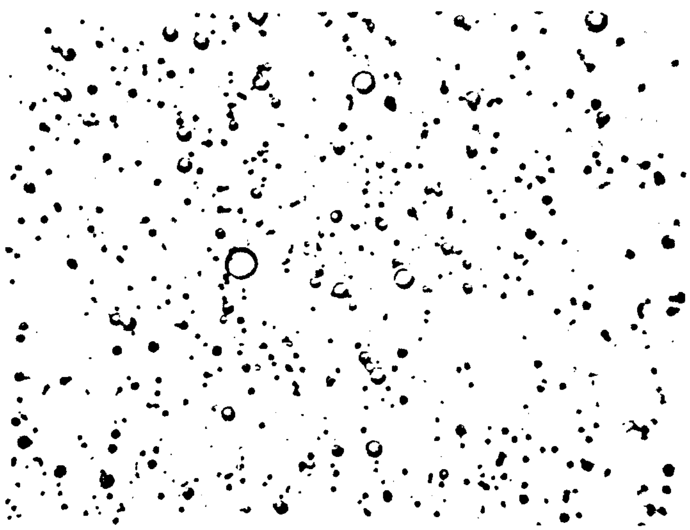


FIGURE 29 PHOTOGRAPH OF THE FINAL DESIGN ENERSEC UNIT



(SAMPLE A)



(SAMPLE B)

FIGURE 30 PHOTOMICROGRAPHS OF NUMBER 4 FUEL OIL EMULSION TAKEN AFTER PRODUCTION (SAMPLE A) AND TWO HOURS AFTER PRODUCTION (SAMPLE B). MAGNIFICATION 400 X

AD-A092 620 DAEDALEAN ASSOCIATES INC WOODBINE MD F/G 21/4
RESEARCH AND DEVELOPMENT OF AN ON-LINE CAVITATING EMULSIFIER FO--ETC(U)
OCT 80 J T PARKER, A P THIRUVENGADAM N00014-79-C-0084
UNCLASSIFIED DAI-JTP-7819-001-TR ONR-CR-169014-1 NL

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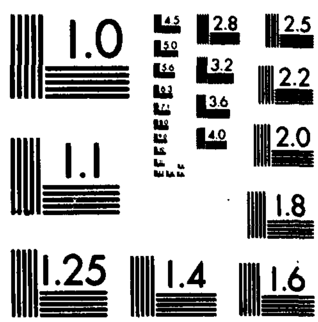

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

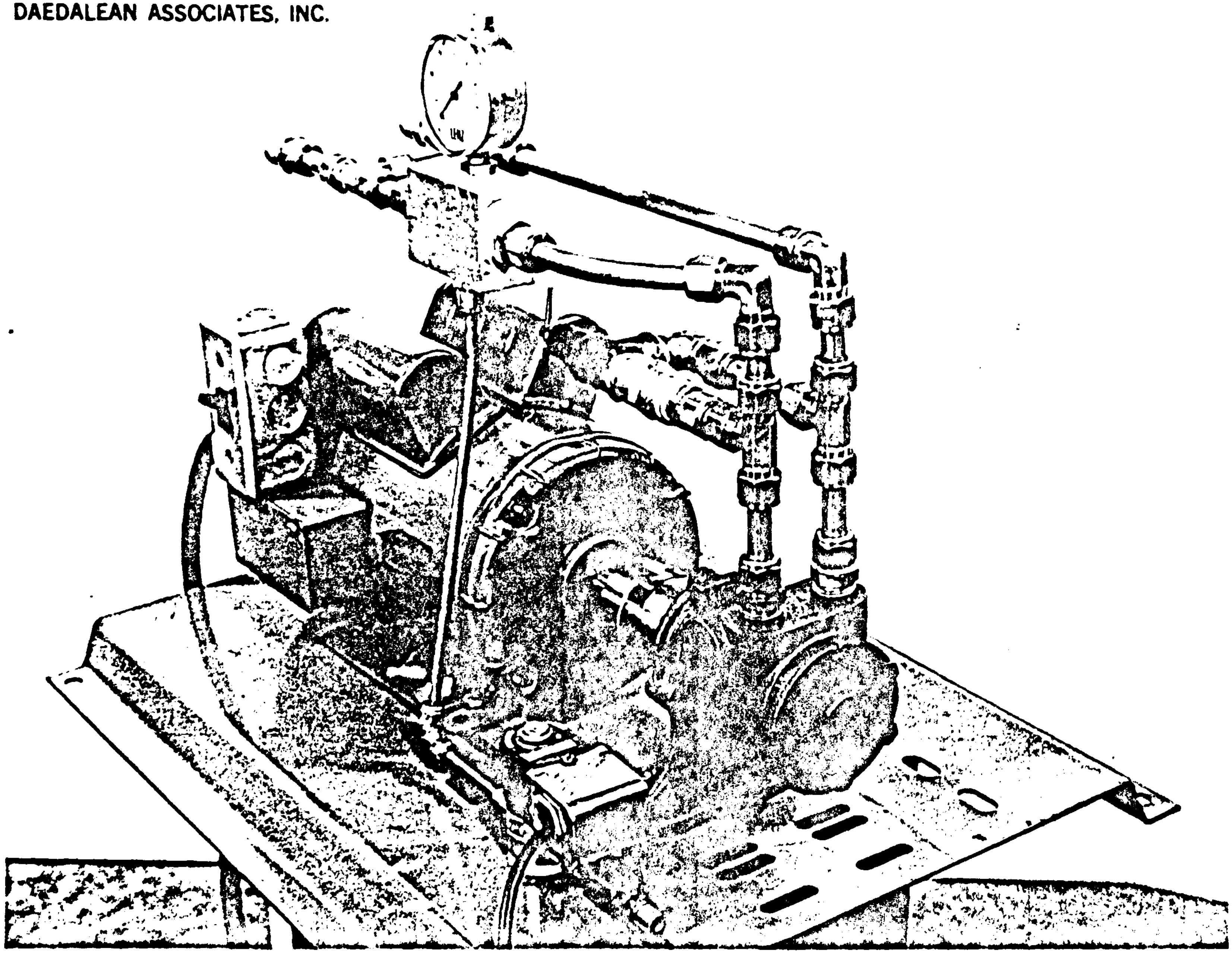

FIGURE 31 PHOTOGRAPH OF THE 5 GPM ENERSEC SYSTEM CONSTRUCTED AFTER THE MINIATURIZATION DESIGN EFFORTS

DAEDALEAN ASSOCIATES, INC.

FIGURE 32 PHOTOGRAPH OF NUMBER 4 FUEL OIL IN COMBUSTION

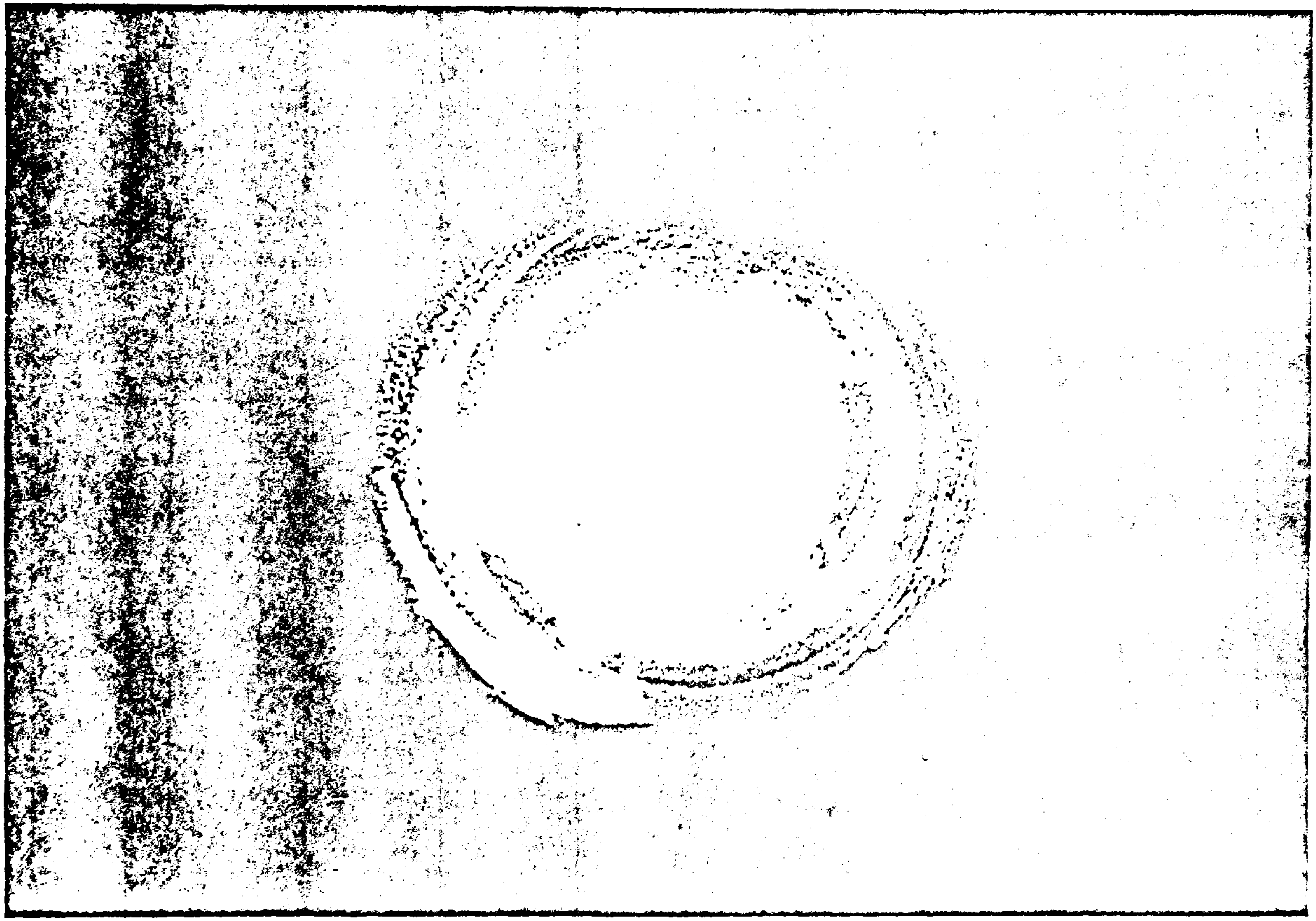

FIGURE 33 PHOTOGRAPH OF THE SAME BURNER WITH EMULSIFIED NUMBER 4 FUEL OIL IN COMBUSTION